Doctor of Philosophy

Complexity of Construction Supply Chain Management: Agent-Based Simulation of High-Rise Building Construction Project

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Based on reductionist perspective, existing researches on construction management have focused on individual components of construction projects under the assumption that those components are independent with each other and the relationship of the input and output of each component is linear. However, production systems of construction projects are complex systems whose components are interdependent and generate emergent effects that is difficult to explain with the properties of individual components. Hence, previous researches with the reductionist perspective have a limitation to understand the characteristics and behaviors of whole production systems. Based on a holistic perspective in order to overcome these limitations, supply chain management regards various types of value-adding and non-value-adding activities as one process and synchronizes such processes in the light of the interdependence of components and processes, in order to maximize the performance of construction projects.

High-rise building construction projects, whose number remarkably in-

crease in the world, are characterized by large-scale projects that comprised of a number of organization, tasks, materials, spaces and information, and concurrent construction projects that a number of construction works are performed simultaneously. Whereas, these projects are also characterized by insufficient resources for material supply. These characteristics can make supply chains of high-rise building construction projects complex by causing various types of interactive and dynamic behaviors between construction and material supply processes. Nevertheless, previous researches on building constructions have been conducted under the reductionist perspective, and researches in the holistic perspective have made efforts to build a theoretical and research foundation, which is difficult to provide specific and quantitative information on the interdependence of components and their emergent effect on a whole system.

For those reasons, in this dissertation, I conducted a series of researches with the purpose of identifying complex behaviors of the components of high-rise building construction projects and examining an emergent effect of a whole supply chain. Through the process to achieve this purpose, firstly, I developed a conceptual framework for construction supply chains and established five hypotheses on the complexity of them. Secondly, using agent-based and discrete-event simulation methods, I developed multiple simulation models associated with the five hypotheses. Finally, I carried out simulation experiments with real-world data in order to confirm the five hypotheses.

Through the results from simulation experiments, this research resulted in the following findings: (1) as the network of construction process is comprised of heterogeneous and locally connected components, the local effects from external risk factors such severe weather do not have a linear relationship with the performance of construction production systems; (2) in the case that insufficient resources are shared by multiple material supply process, the interference between those processes can occur unpredictably and have a negative effect on a whole construction project, even in Just-In-Time method that is able to optimize the inventory level of individual process; (3) spatial

conflicts between workspace and internal material storage space can have a negative effect on a whole supply chain, which is irregularly circulated in the form of feedback between construction and material supply processes; (4) in construction projects that have the complex behaviors as above, holding the minimized inventory level in Just-In-Time results in lower performance due to lack of safety inventory that can alleviate the negative effects of the complex behaviors. However, holing an excessive inventory level also exhibits lower performance because the complex behaviors increase with the increase of the inventory level. Thus, the relationship between the inventory level and the performance of construction projects is not linear; finally, (5) as the external risk factors can changes the behaviors and relationship of system components, the relationship of the inventory level and the performance of construction projects is not constant, but changeable.

The main contribution of this research is to extend a body of knowledge by investigating the complex behaviors of construction supply chains and their impact on the performance of construction projects, which are difficult to explain though the previous researches based on reductionist perspectives.

Keywords: Construction Management; Supply Chain Management; Production System Management; Complex System; Agent-Based Simulation; High-Rise Building Construction Project

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Chapter 1. Introduction

1.1 Theoretical Background

"The whole is greater than the sum of its parts."

- Aristotle -

In science and engineering, reductionism has been the prevailing perspective on research. A reductionist approach signifies that the whole system of interest can be divided into multiple components whose behaviors are predictable with simple linear formulas (Malanson 1999). This reductionist approach influences a large number of areas of modern science and engineering such as physics, chemistry, biology, and economics, and the researchers have made a number of efforts in identifying characteristics of components and tried to understand properties and behaviors of the systems.

Also in construction industry, reductionist thinking has been the basis of the construction project management. Koskela and Howell (2002) referred to this perspective as 'transformation view'. According to his researches on the taxonomy of construction project management, the transformation view regards a construction project as a conceptualized transformation that consists of the relationship of inputs and outputs, and the total transformation can be

hierarchically decomposed into smaller transformations (Bertelsen 2003; Brodetskaia and Sacks 2007). In this perspective, the way to maximize effective performance of the total transformation is to maximize the performance of each decomposed transformation. The reductionist perspective have provided meaningful insights to understand the complex world and its parts, and the previous efforts based on this perspective have made dramatic improvement in a production system of construction projects.

However, it is more and more recognized that our world is not so simple that some phenomena at a system level are difficult to be explained by the properties of individual components (Heng 2008). Overcoming this limitation of the reductionist approach and obtaining a better understanding on our worlds, scientists and engineers begin to pay attention to a holist approach. In the holist perspective, the whole system is so complex that it cannot be explained from its parts, because those parts are interrelated and interdependent of each other (Bertelsen 2003). Based on this holistic view, a theory on complexity and complex system has been received a lot of attention by researchers who attempted to understand the behaviors of the whole system that was unpredictable under the reductionist view. The terms, complexity and complex system, have been used by many researchers, however, it is difficult to find a consensus definition of the complex system (Williams 1999). Instead, researchers have made efforts on of identify characteristics of complex systems in order to investigate what kind of system-level phenomena emerges from what kind of behaviors among components. One of the

most representative features of complex systems is emergence. Emergence means that the collective behaviors of the whole system, which are generated by the interaction of individual components (Heng 2008), cannot be deduced from the properties of individual components consisting the whole systems. Based on this basic concept, researchers have tried to deepen an understanding on various systems.

Researches in construction industry have also made various efforts to understand a construction project in the perspective of complexity (Baccarini 1996, Williams 1999; Bertelsen 2003; Bertelsen et al. 2006; Xiao et al. 2016). Influenced by Shingo's research (1988) regarding lean manufacturing, Koskela (2000) proposed Transformation-Flow-Value (TFV) model for project-based construction production. In TFV theory, a construction project is comprised of flow processes, which means a process of sequential transformations and are distinguished from individual transformations that is independent parts of a system. He identified various flow processes in construction projects, not only tangible flows such as material and equipment, but also intangible flows such as, construction work, information, and location (Arumugam and Varghese 2014). Bertelsen (2003) argued that in flow processes of construction projects, the non-linear and unpredictable phenomena can occur and it is difficult to explain them through individual transformations.

Continuing Koskela's TVF theory, researchers in construction industries

have made large efforts to apply the concept of supply chain management (SCM) to construction projects. SCM is a managerial concept on interconnected activities that are involved in upstream and downstream flows of product, services, finance, and information from suppliers of raw materials to end users of finish goods (Christopher, 1992; Mentzer et al. 2001; Min and Zhou 2002). Even though many researchers regard SCM as an extension of logistics management, SCM is a broader concept regarding production systems beyond logistics (Cooper et al. 1997). Vrijhoef and Koskela (1999) addressed that SCM is a method to manage a logical continuity of production systems including both value-adding activities and non-value-adding activities. Based on the concept of SCM, many researchers continue attempting to understand the complexities of construction projects that cannot be deduced by individual parts of them.

1.2 Supply Chain of High-rise Building Construction

High-rise buildings, as a symbol of economy and technology of modern cities, has been widely spread in the world. According to the Council on Tall Building and Urban Habitat (CTBUH 2015), the completions of buildings higher than 200 meters increase by around 70 percentage every five years since 2001. Along with the increase of high-rise building constructions, researchers' interest in production systems of high-rise building constructions are also growing in order to increase the project's performance. High-rise

building constructions have many similarities to other types of building constructions in many ways, but also have various distinct characteristics and problems from them. The characteristics of high-rise building constructions are as follows.

(1) Large-scale construction: high-rise building constructions are large-scale projects, which are comprised of a large number of components and sub-system, such as construction works, material supplies, resources, and information. Those components and subsystems are basically interdependent on each other and their characteristics vary as regards how they react to external and internal conditions. Thus, it is difficult to explain behaviors of the whole construction project system using properties of each components and sub-system.

(2) Concurrent construction: as large-scale constructions are generally under pressure of time, multiple types of construction works are carried out simultaneously in order to shorten construction duration, so that, construction managers should control a large number of system components (i.e., construction process and material supply process) at once (Arditi et al. 1994). Consequently, there is a high possibility that the interrelationship of components becomes more complicated.

(3) Resource-constrained construction: high-rise constructions are generally performed in urban area, therefore in many cases; these construction

projects have trouble in securing resources for material supply, such as yard storage space (Thabet and Beliveau 1994) and hoisting equipment (Park et al. 2011). Insufficient resources make the complex relationship between material supply processes that have to use the same resources. In addition, it also make an impact on simultaneous construction processes that needs those construction materials.

What can be inferred from these characteristics is that the components of high-rise building construction projects (e.g., construction activities, material deliveries) are significantly interrelated with one another and due to their behaviors, complex problems can be incurred during construction. In order to understand the behaviors of construction production systems, therefore, it is significant to examine the relationship of components and their impact on a whole construction system.

1.3 Problem Statement

A number of the previous studies have made efforts to understand supply chain and production process in building constructions. According to the scope of research, previous studies on high-rise building constructions can be categorized into three groups as shown Figure 1-1. The first group includes researches to improve the performance of a single task of construction projects. For example, some researchers proposed improved methods for

layout planning (Hegazy and Elbeltagi 1999; Sadeghpour 2006; El-Rayes and Said 2009; Park et al. 2011) and hoist planning (Rodriguez-Ramos and Francis 1988; Zhang et al. 1999; Leung and Tam 1999; Al-Hussein et al. 2005; Park et al. 2013).

The second group includes studies that focused on the concept of a flow process in construction projects, but focused on a singly type of construction materials and construction works, such as ready-mixed concrete (Tommelein and Li 1999; Min and Pheng 2007), precast concrete (Pheng and Chuan 2001)., rebar (Polat et al. 2007), and Heating, Ventilation, Air Conditioning (HVAC) (Holzemer et al. 2000).

The last group have attempted to explain the complex phenomenon resulting from the interaction of multiple flow processes, however, they considered single type of flow processes (Polat et al. 2007). Whereas, production systems of construction projects are comprised of various types of flow processes such as construction process, material supply process and information process.

Those studies in three classes have contributed to understand components of building construction projects and improve the performance of them. However, as those studies stand the reductionist approach, they have limitations to explain how and to what extent the interdependent components of construction projects influence the whole construction systems.

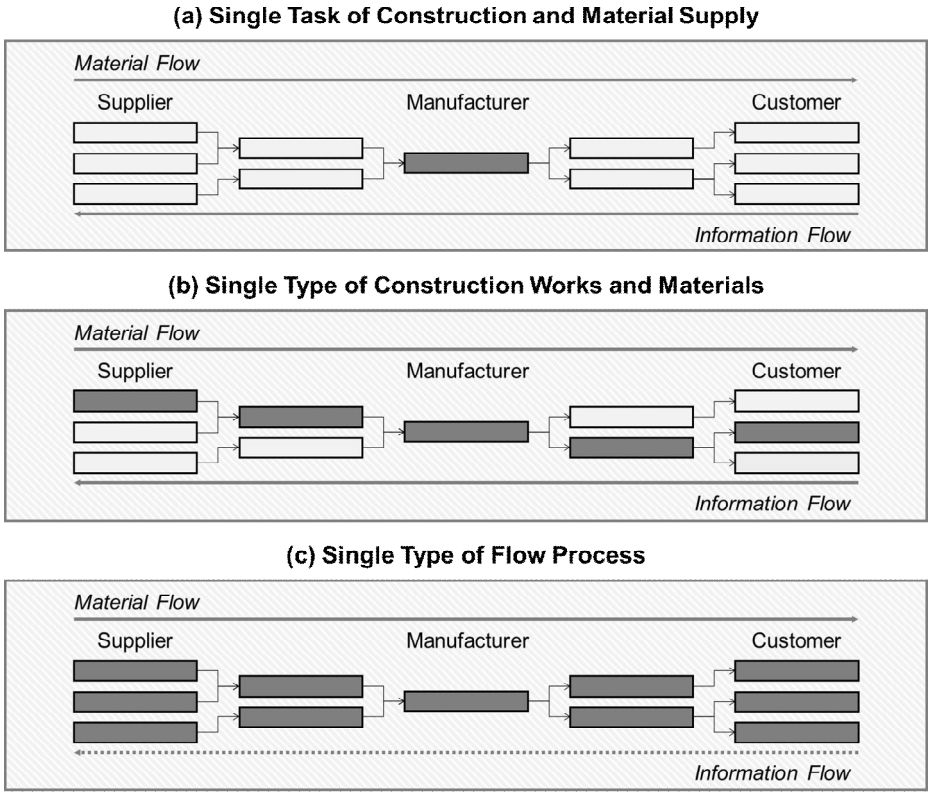


Figure 1-1 Three categories of previous researches on supply chains of construction projects

In additions, several studies (Bertelsen and Koskela 2005, Bertelsen et al. 2007, O'Brien et. al.2008) have tried to understand a construction project based on the perspectives of holism and complex system. These studies have identified dissimilar types of flow processes and concerned the possibility that the interaction and interdependence of these flow processes generate unpredictable effects at a system level. However, these studies focus on building a theoretical framework and include little specific explanation with empirical cases, such as what kind of complex behaviors occur between pro-

ject components and how and to what extent what those behavior affect the performance of construction projects. For such reasons, it is a very challenging issue to investigate complex behaviors of components of construction projects and to examine their effect on the project's performance.

1.4 Research Objectives

The primary objective of this dissertation is to examine complex and dynamic behaviors in construction and material supply processes in high-rise building constructions and their emerging effect on the project's performance.

To achieve this main objective, three specific goals are set up as follows.

(1) Develop a conceptual framework for construction supply chain management: in order to investigate the complexity of construction supply chains, it is necessary to develop a conceptual framework that defines components of construction projects and their relationship.

(2) Develop simulation models that represent complex behaviors of construction supply chain: based on the developed conceptual framework, quantitative models that have the capability to analyze the complex behaviors associated with the pre-mentioned five hypothesis.

(3) Investigate complex behaviors in supply chains of high-rise building constructions through the simulation experiments: using input data from a real high-rise building construction, simulation experiments are carried out to confirm the complex behaviors. Discussions are also conducted to clarify findings and limitations from the results of those experiments.

1.5 Structure of Research

This dissertation is comprised of eight chapters and the details of each chapter are as below.

Chapter 1. Introduction: this chapter covers the background, problem statements, objectives, and structure of research.

Chapter 2. Preliminary Study: this chapter provides an overview of previous researches on the complexity in the context of construction supply chain management and establishes five hypotheses in order to achieve the main purpose of this research. This chapter also provides a description of a conceptual framework of construction supply chain and a literature review on simulation methodologies that have the capability to model complex behaviors of construction supply chains. The following five chapters have aims to conduct a study on the five hypotheses, respectively.

Chapter 3. Impact of Severe Weather Conditions on Concurrent Construction Processes: this chapter presents a study that examines the effect of severe weather condition on a construction process, of which multiple types of construction works are performed simultaneously. In this study, a construction process is considered as a complex system that is comprised of construction activities that differ in the relationship of weather factors and that is locally connected to one another. Through simulation model development and a case study, this study provides a discussion on the emerging effect resulting from concurrent constructions and severe weather conditions.

Chapter 4. Interferences between Material Supply Processes Resulting from Sharing Supply Chain Resources: this chapter presents a study that examines the interference among different types of material supply processes, which results from limited supply chain resources such as yard storage space and hoisting equipment. In this study, a material supply process is regarded as a complex system, which consists of various supply channels that differ in type and amount of resource occupied. Through simulation model development and a case study, this study provides a discussion on what kind of effects emerge from the interferences in material supply process.

Chapter 5. Spatial Conflicts between Construction and Material Supply Processes in Allocating Internal Workspace: This chapter presents a study that examines spatial conflicts between construction and material supply processes, which results from insufficient floor space utilized for both stor-

ing materials and performing construction. This study focuses on the interaction between construction and material supply processes in the process of occupying inside space of buildings. Through simulation model development and a case study, this study provides a discussion on how these spatial conflicts make an influence on both construction and material supply processes.

Chapter 6. Impact of Material Supply Strategy on Complex Behaviors in Construction Supply Chains: This chapter presents a study to investigate how material supply strategy of construction managers relates to construction and material supply processes. Strategy on material supply quantity is able to make an influence on complex behaviors of system's components, which amplify or diminish their impact on production performance. Through simulation model development and a case study, this study provides a discussion on how these spatial conflicts make an influence on both construction and material supply processes.

Chapter 7. Variable Relationship of Supply Chain Strategy and Project Performance according to Risk Environment: this chapter presents a study to investigate a construction system, which have the possibility to change its behaviors, according to the risk environment surrounding construction projects. To do this, the impact of risk events, which are stochastically generated delays in construction and material supply processes, is examined on the construction supply chains.

Chapter 8. Conclusion: This chapter provides a summary of achievements, findings, and contributions of this research. Moreover, this chapter also provides several recommendations for future work stemming from this research.

Chapter 2. Preliminary Study

2.1 Complexity of Construction Supply Chain Management

2.1.1 Complexity and Complex System

Theory of complexity is an attempt to understand a system under the holistic perspective, which is based on the idea that systems and its properties could be understood not as properties of its parts, but as a whole (Boccara 2010). With the holistic perspective, researchers in various fields of science (e.g. mathematics, physics, biology, sociology) have tried to explain complex phenomena of systems of their interest, which had been unexplainable with a reductionist perspective (Mitleton-Kelly 2003, Ladyman et al. 2013). As a result, the theory of complexity is defined not as a single unified theory, but as several theories that arises from various research areas. Researchers are still discussing the definition and properties of complex system. Mitleton-Kelly (2003) summarized the main theories with five research areas as follows: (1) complex adaptive systems; (2) dissipative structures; (3) autopoiesis in biology; (4) chaos theory; and (5) path dependence.

Those theories have attempted to explain the complexities of the systems of interest to each research area and contributed to identify various

characteristics of those complex systems (Ladyman et al. 2013). The keywords on characteristics of complex systems mentioned in the relevant literature are as follows: (1) heterogeneity (Foster and Holzl 2004; Miller and Page 2007), (2) local Interactions (Behdani 2012), (3) Nestedness (Behdani 2012), (4) Adaptiveness (Kauffman and MacReady 1995), (5) Self-organization (Kauffman 1993), (6) Co-evolution (Kauffman 1993; Choi et al. 2001), (7) Path dependency (Choi et al. 2001; Page 2006)., (8) Feedback (Mitleton-Kelly 2003), (9) Robustness (Ladyman et al. 2013), (10) Openness (Xiao et al 2016), (11) Self-Similarity (Mitleton-Kelly 2003), and (12) Emergence (Holland 1999). As these characteristics arose in consideration of different systems, complex systems can be understood in various perspectives. Moreover, complex systems do not need to include all these characteristics, and systems can show the opposite characteristics to some of these characteristics.

In the perspective that regards supply chains as complex adaptive systems, Behdani (2012) identified complex characteristics of supply chains and classified them into two classes: micro-level complexities and macro-level complexities. In his study, micro-level complexities signify the behaviors of system components and the internal structure of systems. The macro-level complexities, on the other hand, means the collective behaviors of the components at a system level. His classification of characteristics of complex systems is shown in Table 2-1.

Table 2-1 Classification of characteristics of complex behavior by Behdani (2012)

Level of Complexity	**Characteristics of Complex System**
Micro-Level Characteristics	(1) numerousness and heterogeneity, (2) local interactions, (3) nestedness, and (4) adaptiveness
Macro-Level Characteristics	(1) emergence, (2) self-organization, (3) co-evolution, and (4) path-dependency

Supply chain management can be understood in various perspectives. For example, supply chains are social systems that include the competitive and cooperative relationships of organizations in supply chains. On the other hand, supply chains are also regarded as production systems that are comprised of tasks such as production and transportation. Behdani's research dealt with the complexities of supply chains that result from the relationship of supply chain organizations, while in this research, supply chains is regarded as production systems. However, two perspectives on supply chains includes many common denominators; therefore, his classification is very helpful to identify the complexities of supply chains.

2.1.2 Complexity of Construction Supply Chain Management

As aforementioned, complex system can be interpreted in various perspectives and have various types of characteristics. In order to achieve the objective of this research, which is to confirm the complexity in supply chain management of high-rise building constructions, it is important to clarify what kind of meanings of the terms, complexity and complex system, can be used in the context of Construction Supply Chain Management (CSCM). Specifically, there are two important questions: what kind of interactive behaviors among system components occur and what kind of system-level behaviors and characteristics can be considered as collective effects emerging from the interactive and dynamic behaviors of components.

Supply chain management covers not only material supply process (i.e., logistics), but also production process, and aims to synchronize flow processes composed of those two processes. Similarly, construction supply chains can be regarded to consist a number of activities involved in a construction and material supply. Thereby, in clarifying the meanings of complexities and complex systems in construction supply chains, two processes, construction and material supply processes, are considered as the main components that induce complex behaviors of construction supply chains. This research focuses on the following characteristics in order to explain the complexities of construction supply chains: (1) heterogeneity, (2) local Interactions, (3) feedback, and (4) emergence.

(1) *Heterogeneity*: the heterogeneity signifies that the property of the components of systems are not identical, but diverse. Thus, each component can exhibit different behaviors responding to identical conditions, according to states of them at that time (Heng 2008). Systems comprised of heterogeneous components may show the different results from those of homogeneous components. Table 2-2 describes the heterogeneity in construction and material supply processes.

Table 2-2 Heterogeneity in construction process and material supply process

Process Type	**Description**
Construction Process	Due to differences of material, equipment, construction method by type of construction work, construction activities receive a different impact from internal and external factors (e.g., severe weather condition), and construction activities, even of the same type of construction work, can have different properties (e.g. height of workspace), which cause different results as a system level.
Material Supply Process	Due to difference of size, weight by material type, the number and amount of resources utilized for material supply process are different. Under resource constrained conditions, the difference in allocating resources to materials can cause the different effect on collective results.

(2) *Local Interactions*: system's components are interrelated. However, in many cases, each component is connected not uniformly with all the other components, but partially with a small number of other components. In this case, it is not acceptable to assume an average value in order to explain in-

teractive behaviors of components (Behdani 2012), and the relationship between a system and its components becomes complex, as the process that the impact of individual components is diffused to a whole system is not simply uniform. Local interactions that can occur in construction and material supply processes are described in Table 2-3.

Table 2-3 Local Interactions in construction process and material supply process

Process Type	**Description**
Construction Process	In concurrent construction, the interaction among types of construction works does occur not among all work types, but among a small number of work types, which are supposed to use the same material, equipment, and space. This local connectivity of construction works can cause different effect on the whole construction process.
Material Supply Process	As construction supply chain converge to a construction site, supply channels interfere with each other in the process of occupying supply chain resource (e.g., storage space, transportation equipment). However, these interferences occur only in the case to use the same resource. In addition, the connectivity between supply channels, even to use the same resource, can be local because period of material supplied varies depending on the relevant construction schedule.

(3) *Feedback*: The behaviors of components influence other components and these influences return to components of origin, which influence the future behaviors of them. The components of complex systems form feedback loops and systems constantly adapt to changing environments. There are two

kinds of feedback loops: a positive feedback loop and negative feedback loop. Positive feedback loops amplify the interactive effects of components and negative feedback loops diminish those effects. Complex systems that consist of several feedback loops exhibit non-linear characteristics, which is difficult to predict through behaviors of individual components (Sterman 2000).

(4) *Emergence*: in complex systems, the collective results of system components exhibit new and unexpected patterns, structures, properties and processes (Holland 1999). These emergent behaviors of systems cannot be deduced from the behavior of an individual component, but the interactive and dynamic relationships of the components.

However, the meaning of emergence is so comprehensive and even covers the meanings of other macro-level complex behaviors. Therefore, before conducting the research on the complexities of construction supply chains, it is necessary to clarify meaning of emergence in consideration of the following questions: what kind of property of whole systems generates emergent behaviors at a system level and what kind of behaviors can be considered as emergent effect that cannot be explained by the properties of individual components. To answer the first question, this research made three classifications according to the system level of construction supply chains and defined which type of components can create complex behaviors in which type of collective variables. Table 2-4 illustrate these classifications.

Table 2-4 Emergence in construction system

System Level	Complex Behaviors	Collective Results
Operation Level (Level 1)	interaction among components comprising of construction process (e.g., construction work and activity)	construction duration
	Interaction among components comprising of material supply process (e.g., supply channel, materials)	lead-time, inventory level
Process Level (Level 2)	Interaction between construction and material supply process	construction duration lead-time, inventory level supply chain cost
	Feedback between construction and material supply process	
Project Level (Level 3)	Change of behaviors of a system and its components according to the extent of risk environment surrounding a project.	

In addition, in this research, these collective properties are accepted to show emergent behaviors in the case that the value, variance, stability, and distribution of these properties are different comparing to those excluding the interactive effect between components.

2.2 Conceptual framework of Construction Supply Chain Management

2.2.1 Characteristics of Supply Chains in Construction Industry

Supply chain management is a management method to synchronize the flows of products, services, and information from suppliers to the final customer in order to overcome the limitations of the existing managerial methods, which optimize individual components, and achieve the optimization of a whole production system (Cooper et al. 1997; Mentzer et al. 2001; Stadtler and Kilger 2008). This method is effective to make a decision such as how many work-in-progress (WIP) and products should be produced during a given period of time, where and how many stocks of WIPs and products should be held, and when they should be transported to the next location.

For a couple of decades, the construction industry has also given an attention of supply chain management and made efforts to embrace this concept (Koskela 2000; 1997 O'Brien; Tserng et al. 2006), in order to overcome the problems that the construction industry faces such as project delays and cost overruns resulting from inefficient on-site production management (Agapiou 1998). However, construction is a project-based production system, therefore, it is difficult to apply supply chain management stemming from manufacturing to production systems of construction industries as it is. Many previous studies (Vrijhoef and Koskela 2000; O'Brien et al. 2008) have tried to sug-

gest a new perspectives and definitions on construction supply chains, comparing distinctive characteristics of supply chains of construction to those of manufacturing. In these literatures, the three primary characteristics of construction supply chains are mentioned as follows.

(1) *Make-To-Order supply chain*: construction is based on project-based production systems. Namely, construction projects begin with contracts in contrast with production systems in manufacturing that mass produces WIPs and finished goods before making contracts with customers (Vrijhoef and Koskela 2000).. Accordingly, the detailed information for producing the final products is provided after making contracts, then, contractors organize supply chains for their construction projects by selecting suppliers and sub-contractors who have the capability to supply necessary materials and services.

(2) *Temporary supply chain*: production systems of manufacturing industries are based on mass-production of which supply chains are set up for long-term and repetitive processes (O'Brien et al. 2008). Whereas, production systems of construction industries are based on one-off construction projects that construct new buildings and facilities of different specifications by project. Therefore, contractors have to organize temporary supply chains with suppliers and sub-contractors newly selected from bidding (Vrijhoef and Koskela 2000). Material supply processes are comprised of similar and repetitive tasks without reference to projects, however, there are no construction

projects under the identical conditions, so that a whole process and its flows are different from project. Because of this, supply chains of construction projects tend to be exposed to unexpected risks, comparing to those of manufacturing and have to make various decisions to optimize and increase the performance of production systems.

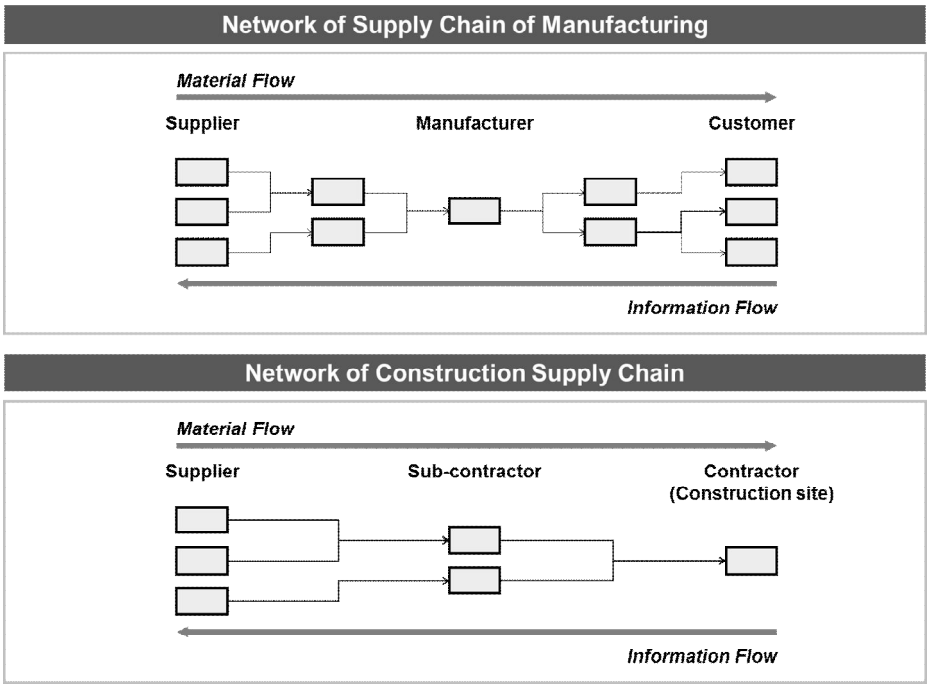


Figure 2-1 Difference of supply chain network between manufacturing and construction industries

(3) *Convergent supply chain*: construction projects are performed in order to produce one or a group of buildings and facilities that are located in the same place. The final products of construction projects (i.e., buildings and facilities) don't need distribution processes. Therefore, in the perspective of pro-

ject management, construction supply chains ends at construction sites, and the networks of supply chains have convergent forms that all supply processes of the construction materials head for one construction site (Vrijhoef and Koskela 2000), as illustrated in Figure 2-1.

2.2.2 Flow Processes in Construction Supply Chains

The three characteristics above are associated with characteristics of supply chains at a project level. In additions to those characteristics, here, this research discusses on characteristics of construction supply chains at a process (flow) level. In consideration of characteristics of construction activities and workspace, this research proposes two additional concepts of flows, the activity flow and space flow, as important elements of construction supply chains.

(1) *Roles of construction activities at the final destination of construction supply chain.*

In supply chains of construction projects, construction activities perform roles, not only as production works that add value to final products, but also as end-users of supply chains that consume delivered materials and generate demand for new material supply. However, the characteristics of construction activities differ from those of end-users of supply chains in manufacturing. Demands generated by end-users are based on the assumption that

there is no causal relationship between end-users and the generation of demands, namely, whether the finished good is supplied to one customer or not have no direct effect on purchases and consumptions of other customers. While, construction activities are carried out along the sequence of the construction process, so that the performance of construction activities directly affect the schedules of other activities, as well as the demand and supple process of materials for them (Figure 2-2).

In addition, production tasks in manufacturing are distributed in supply chains, and they are connected by material flows. Namely, production tasks exchange WIPs and information. On the other hand, even though some construction materials are produced on off-sites (e.g., prefabrication, modularization), construction activities are generally concentrated on construction sites and do not exchange construction materials and information on material delivery. In other words, construction activities have a dependent relationship with material flows; however, they are divided from material flows and comprise their own flow.

To summarize, construction activities and their process have more meanings and roles in supply chains than those of production tasks in manufacturing, and it is necessary to regard them as a flow to be managed at the same level of other flows of supply chains.

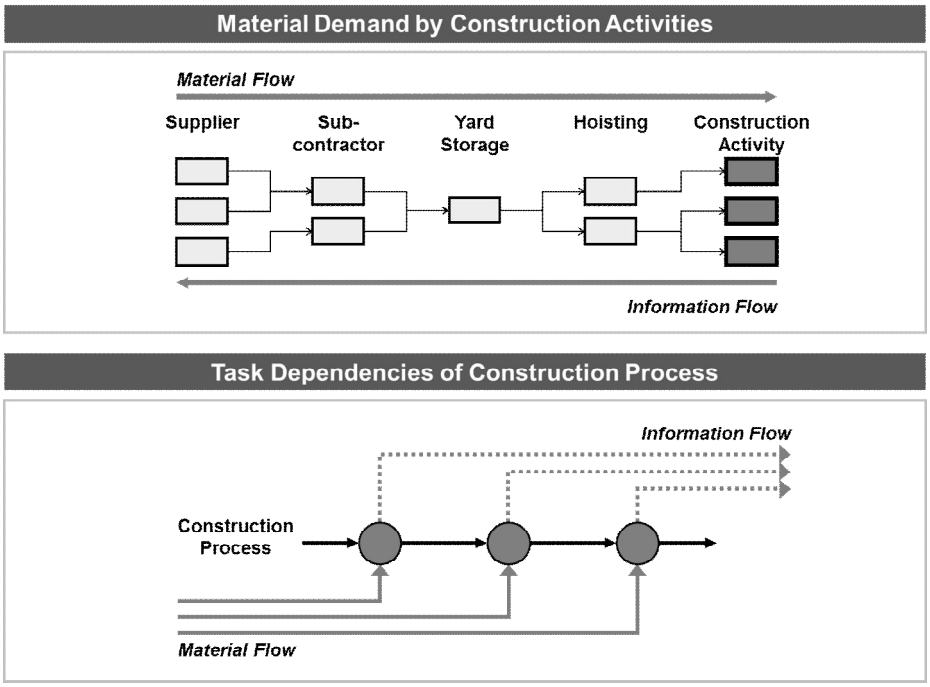


Figure 2-2 Material delivery demand generated by construction activities

(2) *Fixed product and moving workspace of construction activities*

In supply chains of manufacturing, workstations are fixed so that production tasks are performed at the same place and the materials for those production tasks are to be delivered to the same workplace along consistent processes (Tommelein et al. 1999). Thus, production tasks and material supply process can be managed in a simple way under the assumption that they are independent of each other. As there is little possibility for spatial conflicts to occur between production tasks as well as between material supply processes (Figure 2-3A), managing individual tasks and processes may be

effective. On the other hand, in construction supply chains, workspace and path of material delivery are not fixed and continuously changing (Figure 2-3B). Because constructions aim to produce space as the final product, construction activities cannot be conducted repetitively in the same place and have to be moved room to room and floor to floor. Such space usage methods have the possibility to cause spatial conflicts between construction activities and material supply processes, even though they are the same type (Thabet and Beliveau 1994; Akinci et al. 2002). For such reasons, space is an important concept in construction supply chain management and the process of space usage in terms of both construction and material supply have to be carefully controlled and managed.

For these reasons, in addition to material and information flows, activity and space flows are key components comprising construction supply chains.

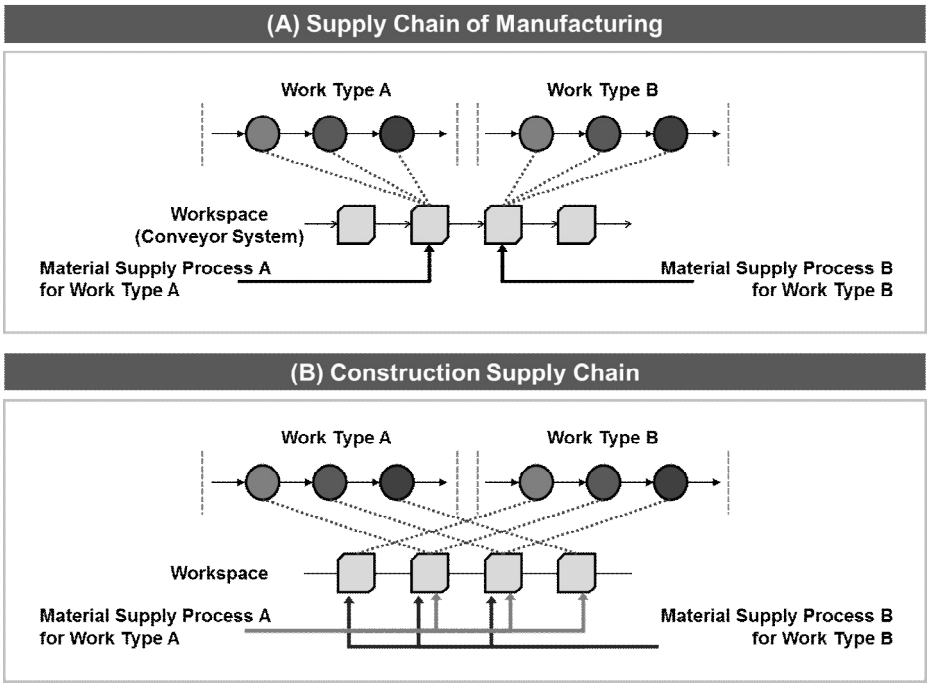


Figure 2-3 Different concepts on workspace in production system of manufacturing and construction project

2.2.3 Development of Conceptual Framework of Construction Supply Chain Management

In the light of the aforementioned characteristics of the construction supply chain, a conceptual framework for construction supply chains was developed with four flows (i.e., material, information, activity, space). The detailed descriptions of four supply chain flows are as follows:

(1) *Material Flow Model*

The material flow in this conceptual framework for construction supply chains has the similar concept to that of manufacturing, which represent a logistic process of products and services. However, there are significant differences between those of construction and manufacturing. The material flow in manufacturing includes not only non-value-adding activities (e.g., transportation, storing), but also value adding activities. These two different types of activities are arranged alternately in the material flow. On the other hand, the material flow in construction supply chains does not include construction activities, which are primary value-adding activities in construction projects, because construction activities are located in the final step of the material flow and the flow occurring between these activities is not involved in the material supply process.

Besides, the material flow of construction supply chains can be regarded as divided into two flows: off-site material flow and on-site material flow. Off-site material flow covers production and transportation process of each material in the factories of suppliers. While, the on-site material flow is comprised of tasks regarding supply of all types of materials at a construction site. All off-site material flows converge to construction sites, so that on-site material flow can suffer from the bottleneck effect that results from lack of resources for material supply. Therefore, in large-scale construction projects, the importance of the management of on-site material flows increases.

(2) Activity Flow Model:

Activity flow is a flow process that is comprised of construction activities and their task dependencies defined in the construction schedule. Construction activities can be executed on the condition that all predecessor activities are completed. After construction activities finish, they also make their successor activities start. Therefore, activity flows can be considered as a flow that prerequisites that trigger the start event of construction activities flow along the network of construction schedule. Apart from task dependencies, construction activities have dissimilar types of prerequisites such as crews, equipment, space, and materials. Among these prerequisites, resources that is utilized repetitively (e.g., crews, equipment) also move along activity flow.

In the case of large-scale construction projects, an activity flow is comprised of several cycles of repetitive construction activities that are performed concurrently. Due to the reason that resources for construction activities are limited and can be used by different types of activities at the same time, activity cycles can interfere with each other and it makes an activity flow more complex to predict. As an activity flow has a decisive effect on demand and supply of construction materials, understanding the total flow of construction activities is critical to controlling a whole production system of construction project.

(3) Space Flow Model

In constructions, spaces are regarded as products that are produced by construction activities. Space is an abstract concept that hierarchically divides buildings and facilities in order to achieve management purposes. Therefore, spaces cannot be transferred as other types of products in manufacturing. Instead, construction activities and resources (e.g., crews, equipment) flow space to space. Namely, in a space flow, states of spatial occupation flow between spaces and the paths of these flows are closely related to an activity flow.

In addition, as construction activities have the purpose to transform spaces, conditions of spaces are changed when construction activities pass through spaces, and these changes can become constraints for other types of the states of spatial occupation to pass through those spaces. Consequentially, it can have a critical effect on an activity flow and material flows and it is very important to understand how construction activities occupy spaces during construction (Akinci et al. 2002).

(4) Information Flow Model

An information flow in this framework has the same concept to that of supply chain management in manufacturing, which is involved in demand and supply of products of individual organizations in supply chains. In the information flow, construction managers monitor the progress of construction

activities for collecting information on demands of construction materials, and determines when and how many materials should be supplied based on their predictions on the construction process and strategies for supply chain management.

Table 2-5 summarizes the flow entity, node, and network type of the four flows.

Table 2-5 Comparison of concepts of four flows

Item	**Material Flow**	**Space Flow**	**Activity Flow**	**Information Flow**
Flow	Materials	Construction crew Occupancy Creation state	Task dependen-cy Prerequisite	Information
Node	Organization Tasks	Space	Activity	Construction managers
Network	Convergent	Hierarchical	Reticulated	Divergent

Figure 2-4 illustrates a conceptual framework of construction supply chains. The system of construction projects consists of the four types of flows, among which form various types of relationships. The material flow and activity flow may be interrupted by external risk factors that are beyond the controllable range of construction managers.

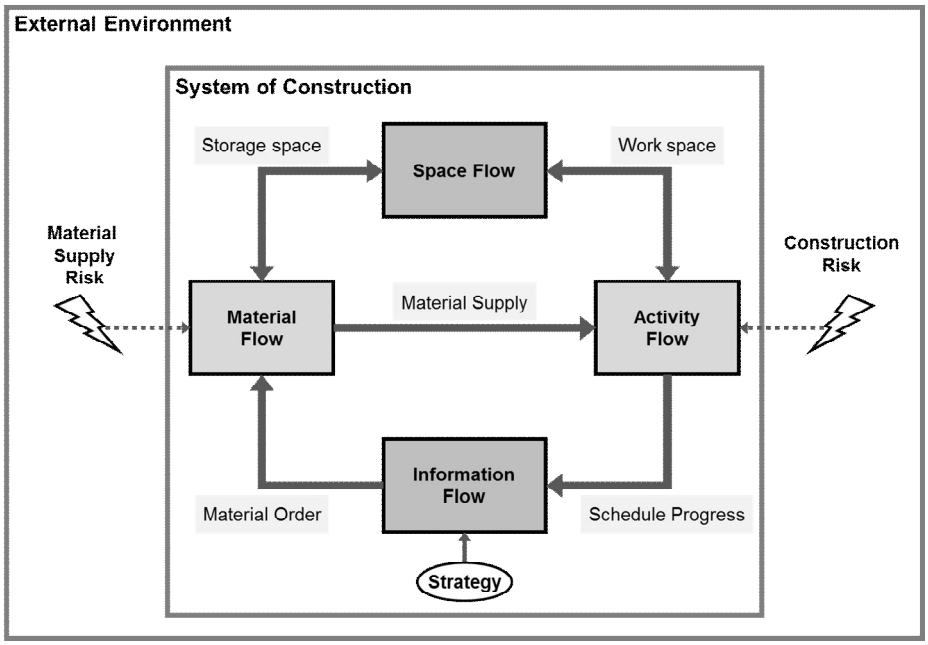


Figure 2-4 Conceptual framework of construction supply chains with four types of flows and their relationships

2.3 Research Hypotheses

In consideration of complex behaviors in construction supply chains dealt with in the previous section, the following five hypotheses are established.

Hypothesis 1: in concurrent construction, the overall duration of construction does not have a linear relationship with the number of severe weather events.

Severe weather has been one of the most representative factors affecting the construction schedule. The impact of severe weather on construction schedule are generally estimated by simply calculating the number of severe weather days with historical weather data. This traditional way is based on the assumption that severe weather events have a uniform effect on all construction activities so that the construction duration has a linear relationship with severe weather events.

In the concurrent construction of high-rise buildings, various types of construction activities are performed simultaneously. These construction activities have distinguishing characteristics due to difference of materials, equipment, and environment related to them, so that severe weather does not have the same effect on all activities. Moreover, as construction activities have a relationship with the small number of other activities on the schedule network, the process that severe weather affects a whole construction may not be simple (Figure 2-5).

The Hypothesis 1 aims to explain that the relationship of a construction process and influence factor can be more complex.

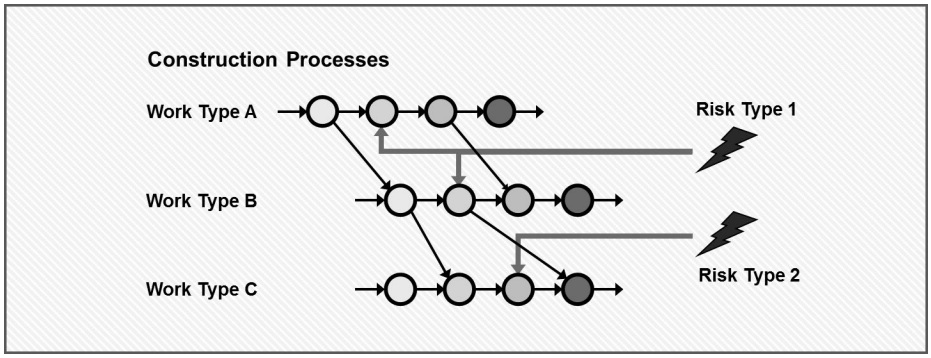


Figure 2-5 Effect of risk factors on heterogeneous and locally connected construction activities

Hypothesis 2: insufficient resources shared by different types of processes result in interferences whose patterns are irregular and which cause a negative effect on construction production system.

Existing methods to control the on-site inventory level calculate the order of for individual material supply processes that minimizes the supply cost and the inventory level in the light of demands. In the case that material supply processes are independent of each other, those methods are based on the assumption that a whole system can be properly controlled by control individual material supply processes in consideration of only properties of each process such as lead-time and demand rate.

However in construction production systems, it is frequently shown that several process have to share one resource due to its insufficiency. Also in high-rise building construction projects, there are many cases that on-site material

supply resources (e.g., yard storage space, hoisting equipment) are shared by a number of material supply process as illustrated in Figure 2-6. In these cases, generally, just-in-time method is applied in order to avoid congestions by minimizing the inventory level. However, this method aims to minimize the inventory levels of material supply processes separately, it is possible that the total inventory level exceed the resource capacity, which can cause a negative effect on construction production system.

This hypothesis is established to examine that in the case that material supply resources are shared, the inventory level can interferences between different material supply processes, which is difficult to estimate due to the variability and have an adverse effect on construction production system.

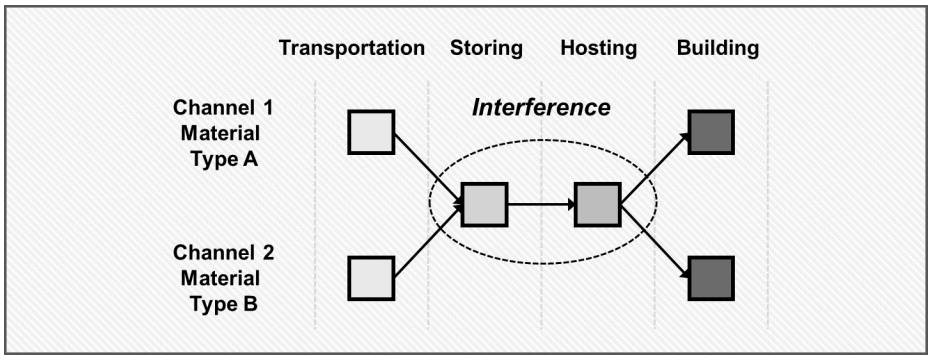


Figure 2-6 Effect of interferences among material supply processes of different types

Hypothesis 3: conflicts occurring between construction and material supply processes have a negative effect on construction supply chain.

A material supply process can adversely affect a construction process in the form of material shortage, while the material supply process is assumed to have no negative effect on a construction process. In other words, when one activity in a construction process is stopped, its successor activities and material supply process related to these activities are also stopped, however, it doesn't mean that when a construction process is resumed, the relevant construction materials cannot be supplied until the execution of those activities so that a construction process is delayed.

In high-rise building constructions, due to lack of outdoor on-site yard storage spaces, materials in yard storage should be transported into internal spaces of buildings as soon as possible, in order to avoid the congestion of yard storage space. However, internal spaces are not sufficient for both material storage space and work space, and it can cause conflicts between construction and material supply processes. The materials of which transportations into internal spaces are delayed by these conflicts remain in yard storages and it can cause a negative effect on material supply processes, consequently, even construction activities that have no relationship with the conflicts (Figure 2-7).

This hypothesis aims to demonstrate that there exist spatial conflicts and it has a negative effect on construction supply chains.

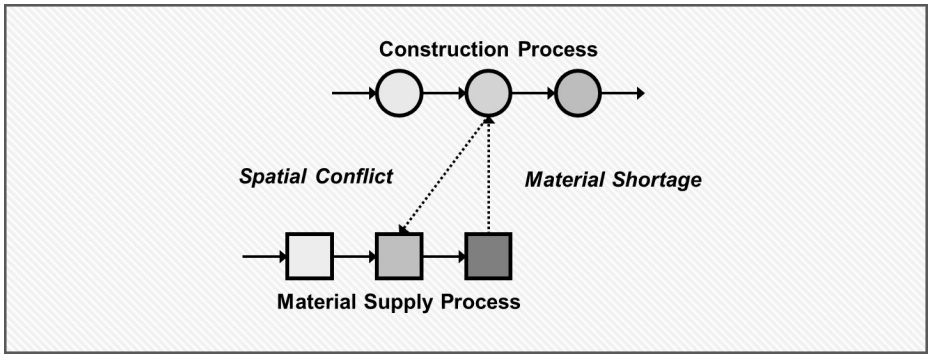


Figure 2-7 Spatial conflicts between construction and material supply processes

Hypothesis 4: the inventory level of on-site materials has a non-linear relationship with an overall duration of construction.

In high-rise building construction projects in which on-site supply chain resources are limited, to control material supply quantity is very significant to construction performance. In Just-In-Time method, on-site inventory are considered as waste to be eliminated in the process of supply chain. Thereby, this method minimizes material inventory level as little as possible and this is a helpful way to avoid the shortage of supply chain resources. On the other hand, in this method, the construction process is very vulnerable to supply risks of materials, because this method does not keep a safety inventory. In other words, if the supply risks are properly controlled, just-in-time, with the minimum level of material inventory, shows the best performance. Hence, the relationship of the inventory level and the performance of construction can be considered as linear.

The construction supply chain is comprised of interrelated components, whose complex behaviors have the possibility to have a negative effect on construction. Accordingly, even if no supply risks of materials occur during construction, construction supply chain can be affected by an inherent effect of itself, and the inventory level could not have a linear relationship with the performance of the supply chain.

The Hypothesis 4 have the purpose to examine the relationship of the performance of construction supply chains and these inherent effects, which cannot be considered under the reductionist perspective (Figure 2-8).

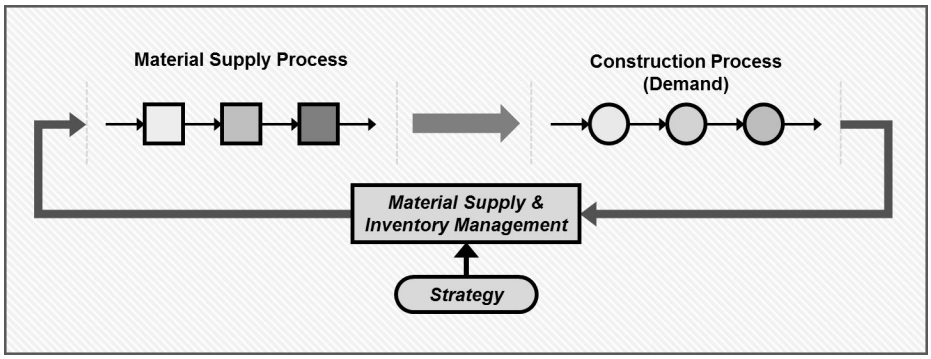


Figure 2-8 Relationship between strategy on inventory level and project's performance

Hypothesis 5: the relationship of supply chain strategy and project performance is not constant, but variable according to external risk conditions.

Construction projects are affected by various types of external risk factors, which varies depending on the environment where the construction projects are performed. Therefore, it is important to identify risk factors and their impact on the performance of construction projects. Reductionist approaches assumes a simple linear relationship between the input and output of systems because these approaches consider systems as static and constant. Therefore, in that perspective, the performances of construction projects are possible to estimate in a simple way to analyze the extent of the risk factors and their linear relationship with the performance. Strategy on construction supply chain also determined under the assumption that they have a linear relationship with the performance and this relationship is not changed by other factors.

However, in the perspective of construction project, a system is comprised of components that interact with each other and dynamically change their states and behaviors influenced by other components' behaviors and environment surrounding the system. Hence, when a system is affected by external factors, the behaviors and the relationship of the system's components can be changed, furthermore, the project's performances expected from the supply chain strategy can also be changed.

This hypothesis is related to the question that the behaviors of construction supply chains and its component are constant and have the same results without regards to external conditions surrounding them.

These hypotheses are related to the complexities in various system levels of construction supply chains (Table 2-4). The hypothesis 1 and 2 focuses on the interactive behaviors between the activity-level components comprising the material supply process and construction process, respectively, and the hypothesis 3 and 4 are related to the interactions between the process level components, namely construction and material supply processes. Finally, the hypothesis 5 is involved in the variation of the behaviors at the system level depending on the external risk environment. In addition, Figure 2-9 illustrate how the five hypotheses have a relationship with the four types of flows in the conceptual model of construction supply chains.

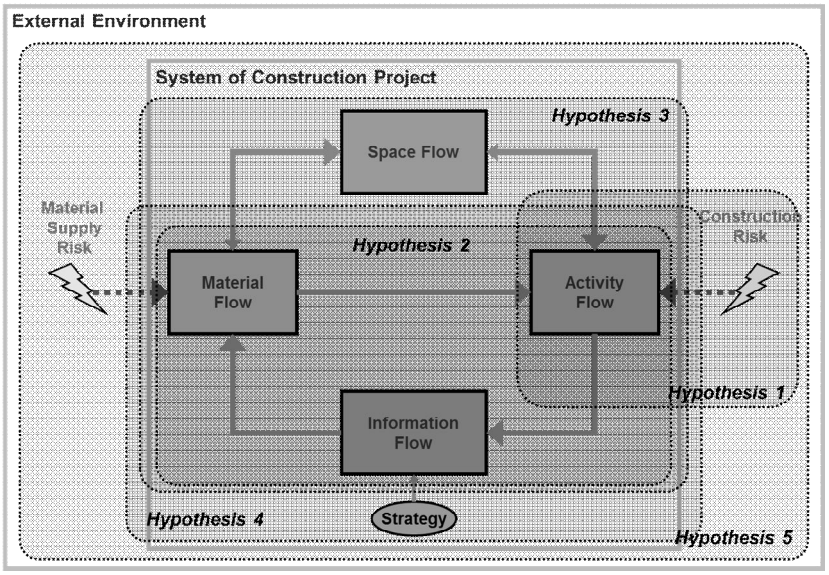


Figure 2-9 Relationship between strategy on inventory level and project's performance

2.4 Simulation Methodologies for Construction Supply Chain Research

2.4.1 Three Simulation Methodologies for Supply Chain Research

Among various research methodologies, a simulation method has undoubtedly played an important role in analyzing supply chain management (Terzi and Cavalieri 2003). First, simulation methods enable researchers to observe the behaviors of systems in the case that it is not possible to apply analytical methods due to the complexity of systems. The complex behaviors of construction supply chains that this research is attempting to investigate is induced by the heterogeneous characteristics, local connectivity, and interactive and feedback relationship of components (e.g., processes and activities) involved in supply chains. In many cases, the impacts of these complex behaviors are difficult to explain using simple mathematical and analytical models. Whereas, simulation methods have the possibility to investigate these effects by reproducing the real world supply chain based on the behavior rules of its components (Tah 2005; Labarthe et al. 2007).

Moreover, simulation methods make researchers possible to analyze what-if problems (Terzi and Cavalieri 2003). It is a very useful way to evaluate the performance of systems, in the case that specific conditions that never occur in the real world are imposed to system and several alternatives exists with different conditions. Construction supply chain, as mentioned

before, is a one-off project-based production system. Even though processes and activities of construction projects are repetitive and similarity by project, there exists no fundamentally identical project. Particularly, high-rise building construction projects have less similarity in shape, structure system, materials, and construction methods and their population is less than other types of constructions. Therefore, contractors are required to evaluate various alternatives that they have never experienced before (Terzi and Cavalieri 2003). As supply chains of construction projects are comprised of a large number of components, there are many kinds of parameters that have to be controlled and it makes researchers difficult to appropriately evaluate alternatives to their systems. While, simulation methods enable these in a logical and effective way.

There are three major paradigms in simulation modeling for complex system (Borshchev and Filippov 2004; Labarthe et al. 2007; Behdani 2012): Discrete-Event Simulation (DES), System Dynamics (SD), and Agent-Based Modeling (ABM). They have different perspective to understand and represent the real world system as follows.

(1) *Discrete-Event Simulation*: DES is a modeling paradigm focusing on discrete events in the real world systems, which are comprised of various states that are dynamically changed by these events (Altiok 2007; Choi and Kang 2013). In DES models, the event list that arranges the discrete events in order of time exists and simulation begins by triggering the initial event in the

event list, proceeds along with the precedence relationship between the events, and ends after all events are activated or there is no events in the event list. Accordingly, DES is a useful modeling paradigm when researchers have an interest of the complexity regarding events and their relationship and can define process before modeling a system.

(2) *System Dynamics*: SD is a modeling paradigm to analyze feedback characteristics of systems. SD was developed by Jay W. Forrester. In order to understand the complexity of a system, he suggested the feedback loop concept and discussed on the system that are comprised of multiple feedback loops interacting with each other (Forrester 1969). In his perspective, the feedback loop becomes a cause of the complex and dynamic behaviors of systems when the impact of one behavior is diffused through the system, returns to the start point of that behavior, and influence the future behavior (Richardson 1991; Sterman 2000). Therefore, SD is a useful simulation paradigm when researchers have the purposes to examine how interactive feedback loops observed in a system influence the performance of a whole system.

(3) *Agent-Based Modeling*: It is difficult to find a universal consensus on a definition for ABM. Borshchev and Filippov (2004) suggested that ABM should be defined by the behaviors of agents in systems, while DES and SD are defined by behaviors and structures of systems. In ABM, behaviors of systems are considered to result from the behaviors of agents who interact

with other agents and their environment and behave according to the behavior rules determined by dynamic states of agents (Epstein 1999; Behdani 2012). Namely, ABM paradigm focuses on behaviors of individual agents at a micro level and their relationships with complex behaviors of systems at a macro-level. Thus, ABM is called a bottom-up modeling method (Axtell and Epstein 1994). In this context, many researchers (Siebers et al. 2010) have discussed on essential characteristics and behaviors of agents that induce complex behaviors of systems: learning ability, communication, spatial awareness, and pro- and reactiveness. Borshchev and Filippov (2004) emphasized that the most essential characteristic of agents is decentralization, which means that the behaviors of agents is not controlled by predefined processes of entire systems, so that the emergence can occur purely according to the behaviors of agents.

Borshchev and Filippov (2004) classified various systems into three categories according to levels of modeling abstraction and discussed on the applicable range of three simulation methodologies. AS the level of modeling abstraction is low, systems deal with exact physical variables (e.g., size, distance, speed, time). Automobile control system and micro traffic system are located on this level. While as the level of modeling abstraction is high, systems are associated with the aggregate behaviors such as global causality and feedback dynamics (Tako and Robinson 2012). For example, systems such as competitive market and population dynamics are included in this level. In their classification, supply chain system is possible to have various

levels of modeling abstraction according to the purpose of management, so that it lies from the middle level to the high level of modeling abstraction.

Moreover, according to their research that discussed on modeling applicability of three simulation methodologies based on their classification, DES is possible to deal with the systems in the low and middle level and SD can represent the behaviors of the systems at the highest level. Whereas, ABM is able to model the systems in the all abstraction levels because agents in ABM is possible to be defined with various scales from objects with physical motion (e.g., particles, cars, people) to the organization (e.g., companies, countries, markets).

Behdani (2012) discussed what kind of the primary characteristics of complex systems can be dealt with by three simulation methodologies (Table 2-6). First, SD is difficult to analyze the micro-level complexities such as heterogeneity and local connectivity that is associated with the changes of behaviors and states of individual agents, because all entities comprising systems have homogeneous characteristics in SD models and models operate with aggregate information of a population of entities such as average and sum. And SD is also difficult to model the nestedness signifying the multi-level characteristics of complex systems. DES is effective to model physical behaviors of complex systems, while it is more debatable to represent the macro-level complexities, such as emergence, because DES defines the processes of systems rather than defines the behavior rules of components, so

that the entities in DES are passive and the behaviors of a whole system are pre-defined before simulation. While, ABM is relatively easy to deal with these complexities because of the decentralized feature of agents.

Table 2-6 Comparison of different simulation paradigms for supply chain disruption modeling (Behdani 2012)

Level of Complexity	**Feature Complexity**	**System Dynamics**	**Discrete-event Simulation**	**Agent-based Simulation**
micro level complexity	Numerousness and heterogeneity	No distinctive entities; working with average system observables (homogenous entities)	distinctive and heterogeneous entities in the technical level	distinctive and heterogeneous entities in both technical and social level
	Local Interactions	Average value for interactions	Interactions in technical level	Interactions in both social and technical level
	Nestedness	Hard to present	Not usually presented	Straightforward to present
	Adaptiveness	No adaptiveness at individual level	No adaptiveness at individual level	Adaptiveness as agent property
macro level complexity	Emergence	Debatable because of lack of modeling more than one system level	Debatable because of pre-designed system properties	Capable to capture because of modeling system in two distinctive levels
	Self-organization	Hard to capture due to lack of modeling the individual decision making	Hard to capture due to lack of modeling the individual decision making	Capable to capture because of modeling autonomous agents
	Co-evolution	Hard to capture because system structure is fixed	Hard to capture because processes are fixed	Capable to capture because structure is modified by agents interactions
	Path dependency	Debatable because of no explicit consideration of history to determine future state	Debatable because of no explicit consideration of history to determine future state	Capable to capture because current and future state can be explicitly defined based on system history

2.4.2 Roles of Discrete Event and Agent Based Simulation Methods in This Research

First of all, what this research aims to do is to examine how the heterogeneous and locally connected components of construction supply chain influence the behaviors of a whole construction project and its performance under the conditions that components interfere with each other due to lack of resources and external factors affect component partially. Hence, DES and ABM will be considered as more appropriate methods than SD that deal with aggregate characteristics of systems.

In addition, behaviors of components in the conceptual framework of construction supply chain management include many fixed processes that can be pre-defined before modeling and controlled by central simulation systems. They are also including some processes that can be changed by inherent interferences and external factors. Accordingly, those processes cannot be pre-defined by fixed relationships of events as DES does. Furthermore, it is difficult to intuitively understand processes that the macro-level phenomena in which this research is interested emerge from individual behaviors of components. Therefore, it is necessary to use modeling methods of ABM. For those reasons, in this research, simulation model will be developed using both methods of ABM and DES, the roles that these two simulation methods played in modeling construction supply chain systems are described in Table 2-7.

Table 2-7 Roles and applications of DES and ABM in this research

Simulation Method	Role	Application
DES	Modeling of processes and behaviors that can be pre-defined by system.	parts of material flow, parts of activity flow
ABM	Modeling of processes and behaviors that cannot be pre-defined by system.	four flow (material, activity, space, information) emergence at a system level

2.4.3 Performance Level of Agent Based Modeling

As aforementioned, agent-based modeling has the significant advantage to solve complex problems. However, due to the nature of complexity, this simulation paradigm also includes some problems with model validation such as to what extent a developed model is possible to appropriately represent the behaviors of system and its components and the results from simulation models are reliable (Klügl 2008; Crooks and Heppenstall 2012).

Axtell and Epstein (1994) summarized the different levels of performance of an agent-based model in this regard, as follows.

- Level 0: The model is in qualitative agreement with the behaviors of agents
- Level 1: The model is in qualitative agreement with the behaviors of ag-

gregates

- Level 2: The model is in quantitative agreement with the behaviors of aggregates
- Level 3: The model is in quantitative agreement with the behaviors of agents

As the Level 0-1 aims to have the qualitative validity, they can be determined through the visualization of the behaviors of individual components or the distributional characteristics of collective behaviors of them. In addition, the qualitative validity of Level 2-3 models can be achieved by conducting statistical analysis routines with empirical data observed in the real world. In this description of the performance level, if a simulation model satisfies the performance criteria at level *N*, it implies that the simulation model also satisfies the requirements for the level N-1. Their taxonomy of agent-based modeling has a significance to provide criteria and methods that researchers have to satisfy in order to achieve the performance level corresponding to their research objectives.

The hypotheses proposed in this research focuses on discovering complex characteristics observable in the behaviors of the construction supply chain and its components, rather than estimating the exact values of systems or finding practicable solutions. Thus, the agent based simulation models that will be developed in this research aims to achieve the performance criteria at Level 1.

Chapter 3. Impact of Severe Weather Conditions on Concurrent Construction Processes

3.1 Introduction

Severe weather events can adversely affect the scheduling of construction projects. Traditional methods have estimated non-working days resulting from adverse weather in the simply way that the number of severe weather days that are calculated using historical weather data are regarded as delays of construction durations. These methods are based on the assumption that a construction process are comprised of activities which have the same characteristics.

However, the process of concurrent construction consists of various types of activities that have the heterogeneous characteristics and local connectivity and are simultaneously conducted with causing interaction with each other. Therefore, each construction activity can be influence by severe weather conditions in different ways; moreover, these local effects could not lead to construction delays. Hence, the impact of severe weather condition on construction schedule may not be calculated in a simple way.

For those reasons, the purposes of this study is to make it explicit that the relationship of severe weather and construction process in order to con-

firm the Hypothesis 1. For achieving this objective, firstly, a simulation model for construction processes and weather effects is developed. For quantitatively estimating the effect of severe weather events in the process of high-rise building construction, two different simulation models are developed and integrated into one model. The first model is a weather generation model, which reproduce synthetic data of vertical weather profiles in consideration of statistical properties of historical weather data. This model is developed using k-nearest neighbor time series resampling. The second model is a simulation model of a construction process, which is comprised of various types of construction activities that has heterogeneous characteristics as regards severe weather and local connections. In this simulation model, construction activities autonomously determine whether they are performed or not in consideration of external and internal conditions for the execution of construction activities, thus, they can properly calculate the effect of severe weather. Secondly, simulation experiments with empirical data are conducted. In order to examine the relationship between the occurrence of severe weather events and construction duration as well as to test the validity of the model, simulation experiments with real data of high-rise building construction project are conducted.

3.2 Severe Weather Conditions and Impact on Construction Activities

3.2.1 Weather Variables and Threshold Values

Construction work can be stopped to prevent safety and quality problems resulting from severe weather. However, weather variables and their thresholds causing activity stoppages vary depending on the type of construction work, since the working environment (e.g., material, equipment, and exposure to the atmosphere) is not the same. Many researchers have made mention of four weather variables pertaining to work stoppages: precipitation, hot and cold temperatures, and wind speed (Lee et al, 2009; Apipattanavis et al. 2010).

Precipitation is the weather factor that most typically causes work stoppages and it influences most types of construction work. In building construction, precipitation can cause slip and fall accidents at high altitudes. When it falls as snow, the degree of danger becomes more critical. Materials and equipment which are sensitive to moisture, such as equipment using electricity, could injure the personnel using them. Extremely hot and cold weather brings the possibility of health problems among construction workers.

In addition, work may also be suspended when the quality of the mate-

rials being used in the construction can be affected by hot and cold temperatures. Construction work using tower cranes for hoisting materials (e.g., steel frames, curtain-wall panels) should also be suspended in extremely windy conditions. Furthermore, strong winds can make it dangerous for construction workers to operate at heights.

In the relationships between construction work and weather variables, it is very important to precisely determine the threshold values whereby severe weather conditions and weather factors cause work stoppages. The threshold values also vary depending on situations where building construction projects are carried out. Even when the work type is the same, weather threshold values can differ due to factors external to the construction methods, materials, and severe weather preparation.

For instance, in concrete placement work, the effects of cold weather can be circumvented or alleviated depending on the materials being used (e.g., chemical admixtures) and cold protection measures (e.g., insulated blankets, heating systems). In addition, governmental regulations pertaining to safety and quality may also include unique clauses according to regional climatic characteristics, applicable where the construction project is being undertaken (Lee et al. 2009). Determining the threshold value is one of the most important issues defining weather activity stoppages and calculating the number of anticipated weather delay days (Nguyen et al. 2010). Therefore, the criteria should be written in consideration of the characteristics of

each construction project, and all parties involved can be in agreement on the weather variables and their threshold values in the criteria.

3.2.2 Degree of Weather Impact

Even when weather variables and threshold values concerning weather delays are identified, the definition of normal weather delays can still be ambiguous because the duration of the work stoppage is not defined. Work stoppages due to severe weather generally last as long as that weather. However, the difficulty of forecasting variations in the weather results in a full day loss of construction, even when the severe weather does not persevere in a day, thus adversely affecting the construction efficiency. There have been many cases where the work stoppage continued even after the severe weather had passed. Finke (1990) classified un-planned works and lingering effects as causes of weather delays, and he argued that delays relating to unplanned works such as reworks to rectify damage and site recovery can be entitled. In addition, weather effects interrupting construction can remain even after the severe weather passes (e.g., snow cover, standing water). He suggests that they all be treated identically as normal work stoppages.

Unplanned work and any lingering effects are decisive in estimating weather delays. For example, the total number of days of weather delay is markedly different depending on whether the severe weather days occur separately or serially, despite there being the number of severe weather days. In

the case of serial weather delays, the total weather delay decreases by reducing repetition of unplanned work and lingering effects. Nguyen et al. (2010) stated that differentiating between the lingering days caused by normal and the abnormal severe weather is important to the definition of normal weather days. They also mentioned that it is simple to count lingering days caused by abnormal severe weather as abnormal severe weather days. However, this approach is also ambiguous in that the number of days that are analyzed with-out any consideration being given to lingering effects leads to a major difference between the anticipated and actual number of days. Meanwhile, Kenner et al. (1998) suggested additional stoppage conditions, with weather variables and threshold values for lingering days depending of the type of the construction work.

3.3 Vertical Weather Generation Model

3.3.1 Weather Generation

A weather generator is a numerical model that reproduces synthetic weather data as a daily time-series of weather variables with the same statistical properties as historical weather data (Richardson 1981, Racsko et al. 1991). This method has been widely applied to various fields such as agriculture, ecology, wind power generation, and the photovoltaic industry, and many types of models and methods have been proposed (Caraway et al.

2014). The weather generation methods are classified according to the treatment of the historical weather data: parametric and non-parametric approaches (Wilks 2009; Lee et al. 2012; Caraway et al. 2014).

The parametric approach, as represented by the model, has a functional form that is completely specified by a small set of parameters that define a specific distribution which fits the historical weather data (Richardson and Wright 1984). WGEN (Weather Generator, Richardson 1981) and LARS‐WG (Long Ashton Research Station Weather Generator, Semenov and Barrow 1997) are representative parametric weather generation models. A large number of developments have arisen to serve the researchers' own purposes with those models, while a loss of cross-correlation among the weather variables has been pointed out (Lee et al. 2012). This is because the precipitation state determines the other weather variables in the simulation process (Rajagopalan and Lall, 1999).

In contrast, a non-parametric approach, as represented by the k-nearest neighbor method (KNN, Rajagopalan and Loll 1999), is a method whereby, given the weather conditions on the current day, one of the most similar days in the historical weather data is randomly selected and a higher probability is assigned to those days that are more similar (Caraway et al. 2014). The main advantage of this approach is that the statistical properties of the historical data can be accurately reproduced because the historical values are only reshuffled and make no assumption when generating weather conditions

(Flecher 2010). Rajagopalan and Loll (1999) conducted a comparison analysis between the parametric model and their non-parametric model and concluded that their model is better at preserving the cross dependence and frequency structure than others. On the other hand, the inability to create new weather conditions, which have never been observed (i.e., climate change), have been mentioned as an important drawback in the literature (Lee et al. 2012).

3.3.2 Vertical Weather Profile

Weather is the state of the atmosphere, which exhibits complex behavior resulting from atmospheric motion, heat and energy circulation, and earth motion (e.g., rotation and revolution). As such, it is very difficult to predict future conditions accurately (Lutgens et al. 1995). Despite the complexity of the weather system, some weather parameters such as temperature and wind speed exhibit typical patterns in the vertical structure (Marshall and Plumb 2008).

Vertical profiles of the air temperature in the troposphere show a pattern where the temperature decreases linearly with altitude, referred to as the lapse rate, because of the heat energy transfer from earth's surface to the atmosphere (Foken 2008). For example, with the international standard atmosphere, the rate of temperature decrease is close to 6.5°C/km, and the dry and saturated adiabatic lapse rates are around 9.8 C°/km and 5 C°/km, respec-

tively, under adiabatic conditions (Lutgens et al. 1995; Mokhov and Akperov 2006). However, the environmental lapse rate, which refers to the altitudinal change in the temperature of the actual atmosphere, varies according to the time and location (Stone and Carlson 1979).

The wind speed profile generally tends to increase with altitude as the surface friction has a negligible effect on wind speed (Foken 2008). The power law wind profile is a mathematical model which approximates the vertical wind profile while considering the surface roughness and atmospheric stability (Arya 2001). Even though the power-law profile is not based on sound theory, it is well-known to fit to the measured wind speed data in the lower part of planetary boundary layer (Arya 2001). Because of its accuracy and usefulness, this power-law profile is well used in various engineering fields. .The power law wind profile is defined as follows:

$$v_z = v_g \cdot \left(z \cdot z_g^{-1} \right)^{\alpha} \ (0 < z_g < z) \tag{3-1}$$

where v_z is the wind speed at height z, v_g is the gradient wind at gradient height z_g, and α is an exponential coefficient, which is based on the surface type and atmospheric stability.

The precipitation falling to earth, regardless of its form, consists of condensed atmospheric water vapor. Precipitation can be considered as requiring

a given condition between the earth's surface and the clouds, such that water vapor in the clouds will fall as precipitation. The clouds that produce rainfall (e.g., nimbostratus, cumulonimbus) are usually found at 2000 km. In consideration of the height of these clouds, there is no vertical variation in the precipitation with altitude at the altitudes at which construction activities are performed.

3.3.3 Vertical Weather Profile Generation Model

To develop the vertical weather profile generation model required for this research, the non-parametric approach using KNN methods proposed by Rajagopalan and Loll (1999) was employed for the following reasons: (1) the construction duration is short enough so as not to be affected by trends in climate change; and (2) this method can be modeled with additional weather variables and provides a better solution to accurately generate vertical weather pro-files while making fewer assumptions. The basic principle of this method is that one of k numbers of days in the historical data, for which the weather conditions are closest to those of the current day, are randomly selected. The historical successor of the selected day then provides the weather for the simulated day. The similarity of k numbers of nearest days is calculated based on the Mahalanobis distance:

$$D_i = (\mathrm{X}_{t-1} - x_i)^T C^{-1} (\mathrm{X}_{t-1} - x_i)^T \tag{3-2}$$

where x_i is the multivariate time series of weather variables, x_{t-1} is the daily value of the weather variables on current day $t-1$, and C^{-1} is the inverse of the covariance matrix of x. The weighting probability w_m for selecting one of the k nearest days is given by:

$$w_m = \frac{1/\mathrm{m}}{\sum_{j=1}^{k} 1/j}, \quad \mathrm{m} = 1, \ldots, \mathrm{k} \tag{3-3}$$

where m is the index of k nearest days.

The weather data has the following six variables: solar radiation (SRAD), maximum temperature (TMX), minimum temperature (TMN), average wind speed (WSPD), average dew point temperature (DPT), and precipitation (P). However, these weather variables do not reflect the atmospheric conditions at height. Thus, additional variables which are estimated from the vertical profile of TMX, TMN, and WSPD are also included in the historical weather data. To estimate the lapse rate of the TMX and TMN profiles, a simple linear regression method is applied. Two pairs of regression and intercept coefficients which most closely fit the vertical profile data of maximum and minimum temperature are estimated. And, the exponential coefficient and the gradient wind in the power-law equation are estimated from the vertical wind speed profile data. With these additional variables, a total of twelve weather variables constituted the proposed weather genera-

tion model.

The vertical weather profile generation model was tested against historical weather pro-file data measured in Paju, South Korea. The historical weather data covered a span of five years and was divided into twelve seasonal groups of the same length of days, and the twelve weather variables described above were prepared from the collected historical data. Furthermore, 25 synthetic records covering five years, which was the same as the length of the historical data, were generated using the proposed model. Using the synthetic weather data, the basic statistics of interest were estimated in order to validate the proposed model using basic statistics.

In Figure 3-1 and 3-2, the mean and standard deviation of the generated vertical profile data (box plot) of TMX, TMN, and WSPD at intervals of 200 m and at altitude in the 1st and 7th seasons are presented together with the historical profile data (dashed line). As illustrated in Figs. 1 and 2, the properties of the weather profile of the historical data are preserved well in the simulation results, whereas the mean of TMN at a height of 0 to 200 m is underestimated relative to the historical data.

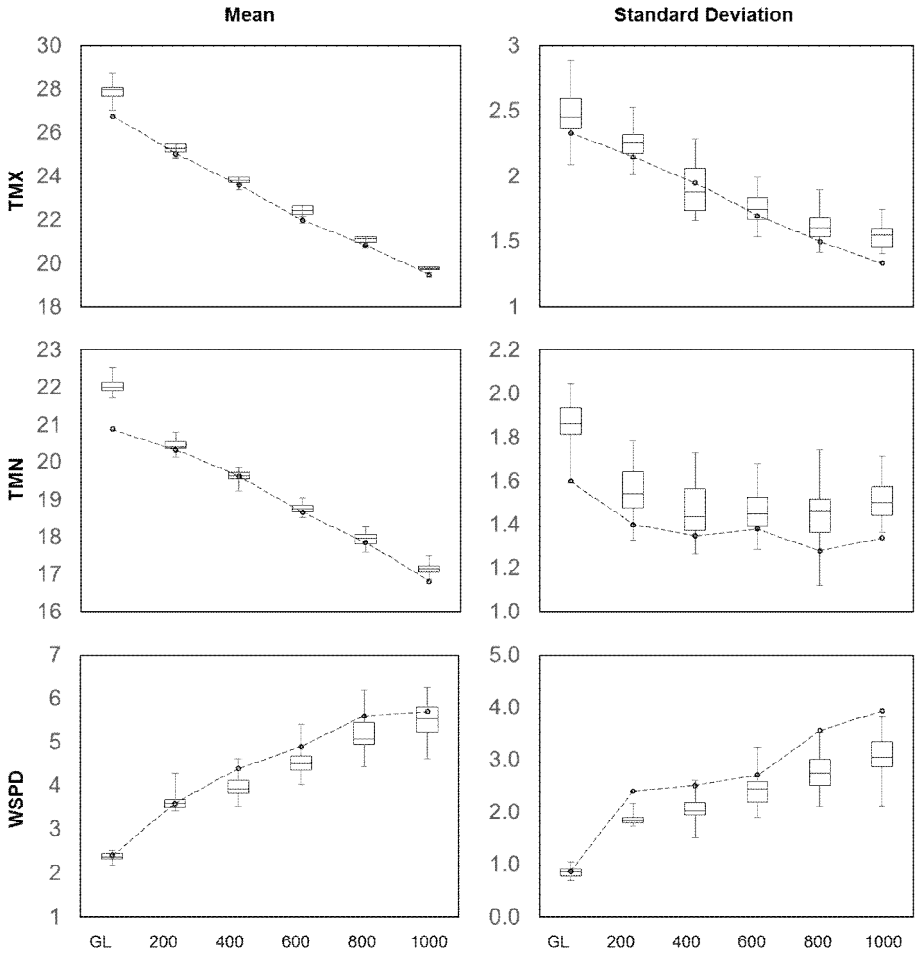


Figure 3-1 Mean and standard deviation of weather variables of historical data (circles) and data generated from model in 1st season (box plots)

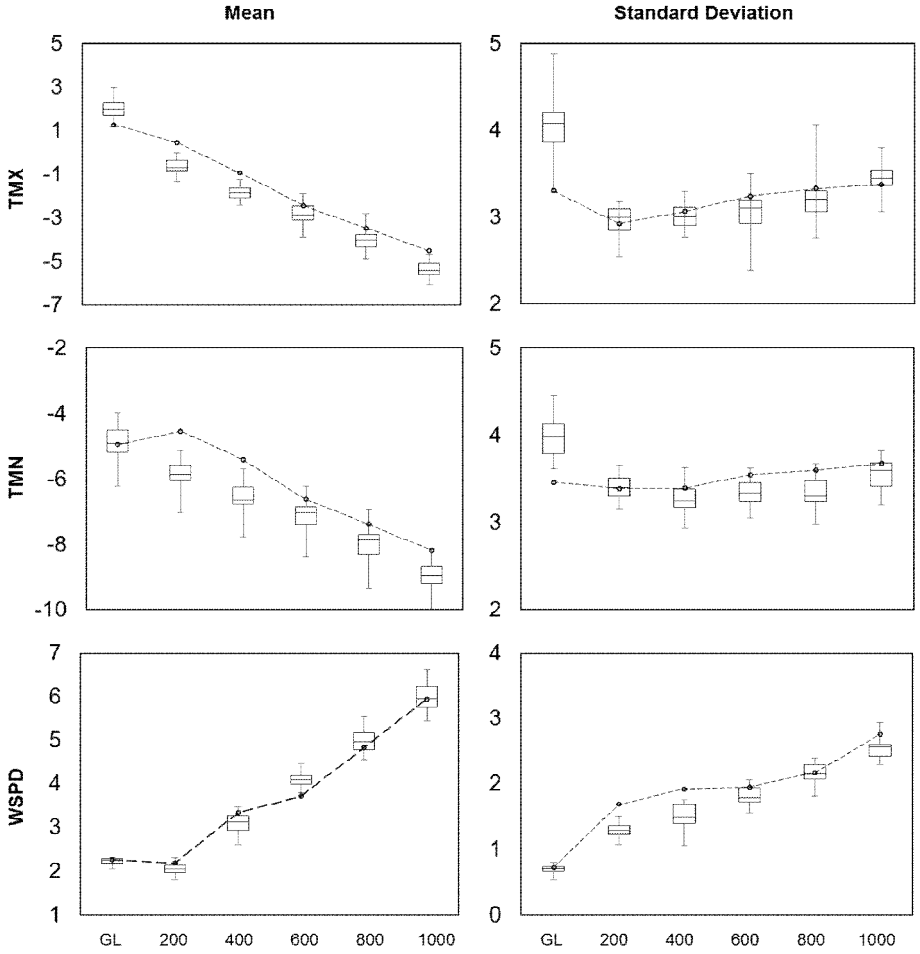


Figure 3-2 Mean and standard deviation of weather variables of historical data (circles) and data generated from the model in 6th season (box plots)

3.4 Model Development

To estimate the length of weather delays in high-rise building construction, a simulation model was developed by integrating the vertical weather

profile generation model described in the previous section with a construction schedule simulation model that uses the discrete-event simulation (DES) method. As shown in Figure 3-3, the simulation model is comprised of the following two components:

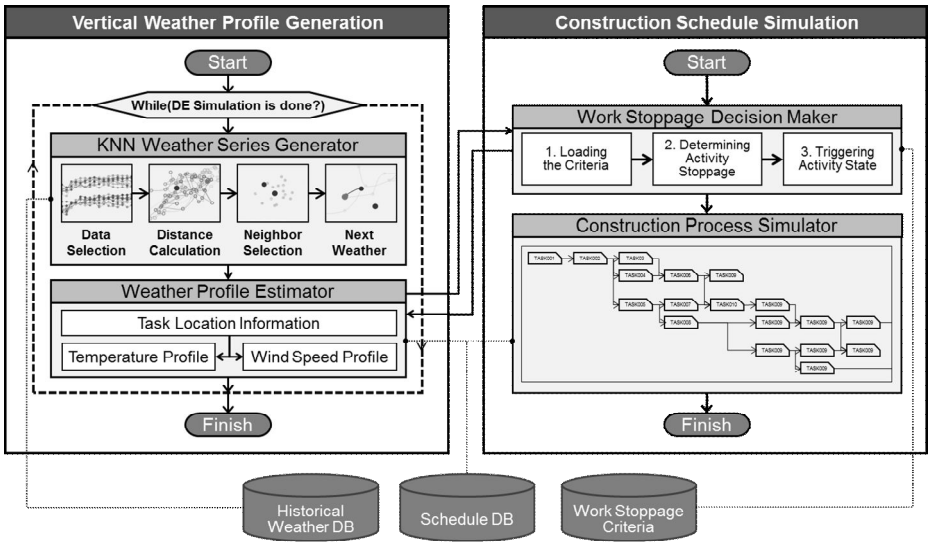


Figure 3-3 Conceptual model of activity flow simulation model with vertical profile based weather generation model

(1) Vertical weather profile generation model which aims to estimate the weather conditions at the altitude at which the construction works is ongoing, with the results being transferred to the next component, that is, construction schedule simulation. The KNN weather series generator in this component repetitively generates a series of daily weather conditions and, based on the results, the weather profile estimator estimates the weather at the height requested by the construction schedule simulation.

(2) The construction schedule simulation includes the construction process simulation model which calculates the start and finish time of each construction activity in line with the construction schedule. The work stoppage decision maker determines whether or not the work can be performed, based on the weather conditions sent from the vertical weather profile generation.

The main issue facing the development of an integrated simulation model is to make the two components compatible with the different time advance methods, namely vertical weather pro-file generation, as simulated in continuous time, and construction schedule simulation in discrete time. For example, when severe weather occurs, the relevant construction activities should be suspended, at least, or if it has already begun, be ceased until the weather effect disappears. However, the DES tools, specialized in construction operation research efforts such as CYCLONE (Halpin 1973), STROBOSCOPE (Martinez 1996) express construction activity with a start event and various conditions (e.g., resource availability, activity dependency) for activity execution; whereas, the finish events triggered depending on time passing as much as the duration of each activity. This becomes a restriction to model the context of weather delay in constructions. Thus, an activity model with additional events and states which can express them was developed in the construction schedule simulation.

Figure 3-4 shows a state chart for the proposed activity model, which draws a comparison with those of abovementioned construction DES tools.

The activity model consists of the states of ‘waiting’ and ‘working’ as well as the events of ‘start’ and ‘finish.’ The proposed activity class includes them. When severe weather conditions interrupt an ongoing activity, the elapsed time counter for the construction is paused and saved until they are no longer affected by the influences acting on them.

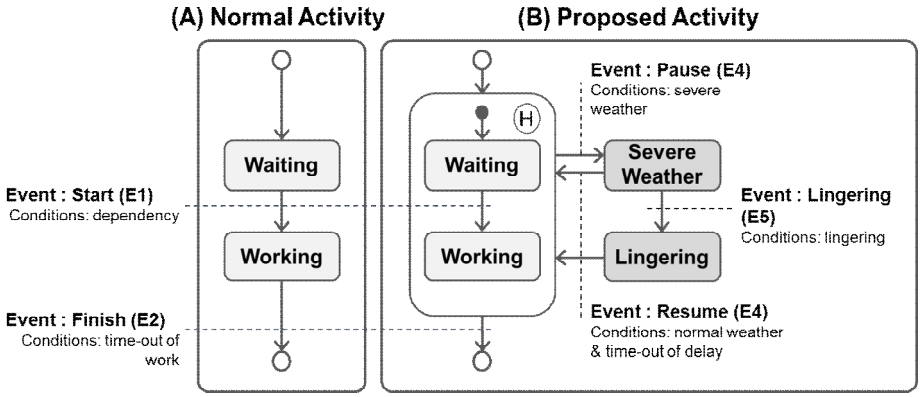


Figure 3-4 State chart of simulation activity class for weather delays

3.5 Simulation Experiments and Results

3.5.1 Input Data Descriptions

The proposed simulation model was tested by being applied to an actual case. The case involved a 50-story high-rise office building construction project located in South Korea. In the case study, the scope of the construction works was limited to the following work types which were directly affected

by severe weather: RC core-wall work, structural steel frame work, deck-plate work, RC work, and curtain-wall work (Figure 3-5). The selected work types are executed sequentially at intervals of 3-6 floors and thus avoiding spatial interference between works. The activity stoppage criteria listed in Table 3-1 were investigated through interviews with the site managers of the case projects.

Table 3-1 Threshold criteria of work stoppages due to severe weather by type of work

Work Type	**Temperature**	**Wind-speed**	**Precipitation**
Common	Heat stroke (above 45℃)	-	Low Efficiency (above 10mm)
Core wall	Concrete placing (below -15℃)	Concrete placing (above 10m/s)	Concrete placing (above 5mm)
Steel Frame	Welding (below -15℃)	Welding (above 6m/s)	Welding (above 5mm)
	-	Lifting (above 10m/s)	Lifting (above 5mm)
Deck Plate	Welding (below -15℃)	Welding (above 6m/s)	Welding (above 5mm)
RC	Concrete placing (below -15℃)	Welding (above 5mm)	Concrete placing (above 5mm)
Curtain-wall	Welding (below -15℃)	Welding (above 6m/s)	Welding (above 5mm)
	-	Installation (above 10m/s)	-

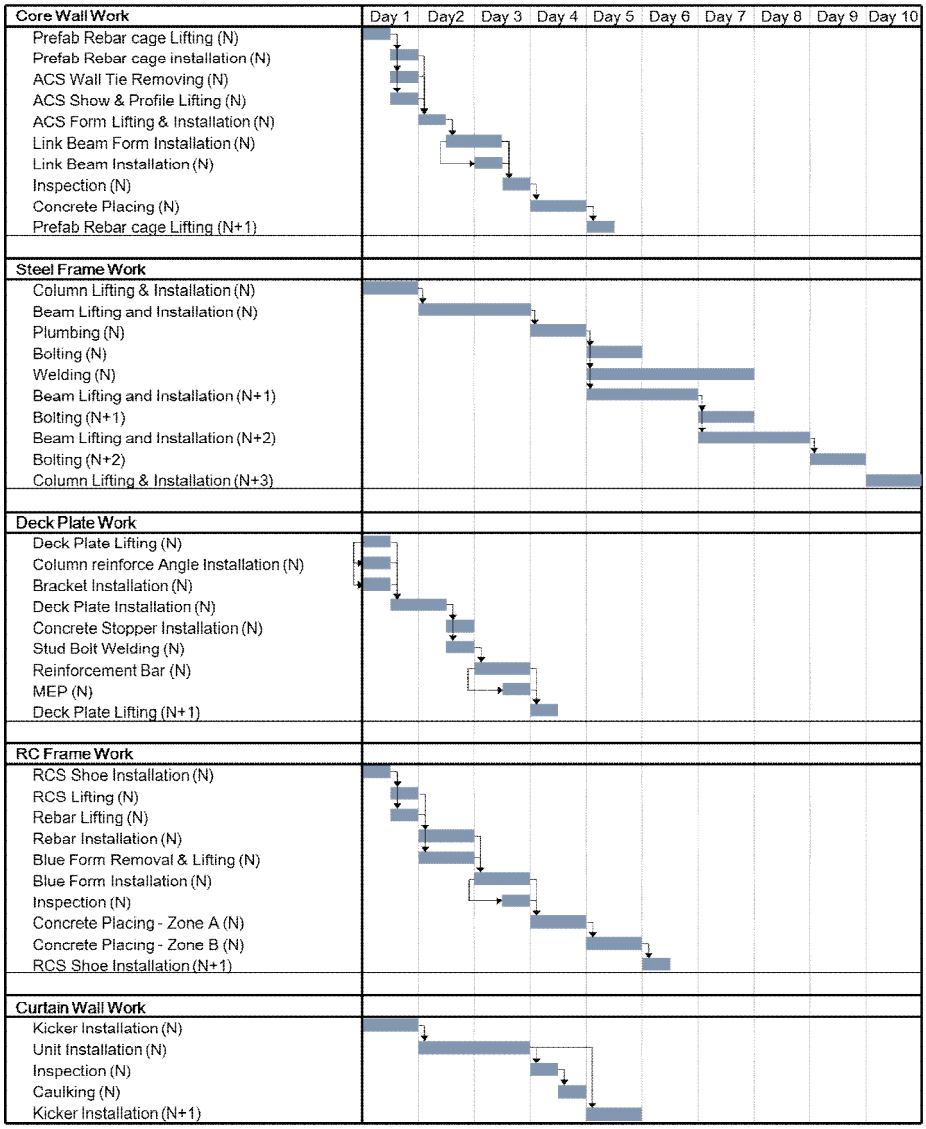


Figure 3-5 Types of work and sequence in schedule of case study

3.5.2 Simulation Results

Analysis 1: Validation Analysis Using Construction Durations

(a) Result 1-1: Comparison of Construction Durations of Actual Schedule and Simulated Results

First, a comparative analysis addressing the simulation and the actual case was conducted to examine whether the developed model reflects the actual process of weather delays in building construction. The simulated results were calculated as average values for 1000 iterations of the simulation, and the work durations for both the simulation and the case indicate a pure working time excluding the temporarily paused duration due to the severe weather. By analyzing the results as illustrated in Table 3-2 and 3-3, the severe weather days and work duration of the simulation are predominantly similar to those of the actual case, even though the results of some work types (e.g., RC and curtain wall) exhibit gaps in the working days. The simulated results did not always show identical results because the observed data from the actual case was only one of many stochastic events.

Moreover, work stoppage and productivity loss caused by other delay factors (e.g., equipment availability, material supply) can cause a cascade effect along the sequence of construction schedule which influences on the activity dependency. Therefore, by means of a comparison between the re-

sults of the applied case and simulation model, we can assume that the process of the simulation follows that of the actual case and can be utilized for reasonably estimating normal to severe weather delays in building construction.

Table 3-2 Working and Non-working days of real construction case

Type of Day	**Core Wall**	**Structural Steel Frame**	**Deck Plate**	**RC**	**Curtain Wall**
Working Days	206	154	132	215	153
Non-working Days	161	161	189	105	144
- Holidays	111	95	99	97	91
- Severe Weather Days	42	50	72	6	51
- Others	8	16	18	2	2

Table 3-3 Simulated working and non-working days by work types (expected values after 1000 iterations)

Type of Day	**Core Wall**	**Structural Steel Frame**	**Deck Plate**	**RC**	**Curtain Wall**
Working Days	201.2	154.6	128.7	199.8	139.1
Non-working Days	139.4	150.2	158.6	107.7	157.2
- Holidays	104.5	88.6	92.2	95.2	90.6
- Severe Weather Days	34.9	61.6	66.7	12.5	66.6

(b) Result 1-2: Impact of Vertical Weather Changes on Weather Delays

With the simulated results shown above, however, the effect of the altitudinal variation in the weather on the construction process is not clear. Thus, the simulated results above were compared to those with the different settings, in which a vertical weather profile is not applied for the weather generation. As shown in Table 3-4, 9.3% to 18.2% of weather delays by the work types and 33.3% of the total project duration were regarded as being delays, which results from the vertical variation in the weather conditions. This comparison shows that without any consideration being given to the vertical weather variation, the anticipated number of normal severe weather days and their effects can be misestimated in high-rise building construction projects.

Table 3-4 Weather delays in ground based weather and vertical profile based weather

Work Type	**Weather Delays**			**Proportion [A/(A+B)] (%)**
	ground based weather delays	**vertical profile based weather delays**	**Total**	
Core Wall	28.6	6.3	34.9	18.1
Structural Steel Frame	54.8	6.8	61.6	11
Deck Plate	60.4	6.2	66.7	9.3
RC	10.3	2.2	12.5	17.6
Curtain Wall	58.6	8.0	66.6	12.1
Project	29.7	14.8	44.6	33.3

Analysis 2: Relationship of Adverse Weather Events and Construction Process

(a) Result 2-1: Time Series Pattern of Weather Delays by Weather Factors

Finally, the time series data for the monthly weather delays arising from the weather variable was analyzed as illustrated in Figure 3-6. The weather delays caused by precipitation show a similar pattern in a one-year cycle, whereas the delays due to wind speed rarely occur in the first year but increase rapidly from 10th month until the 14th month. As aforementioned, the

seasonality is a natural characteristic of the weather, and the existing method is based on the assumption of this characteristic. However, the analysis results indicate that there is the possibility of not following such that the seasonality, particularly in terms of the wind speed, is good.

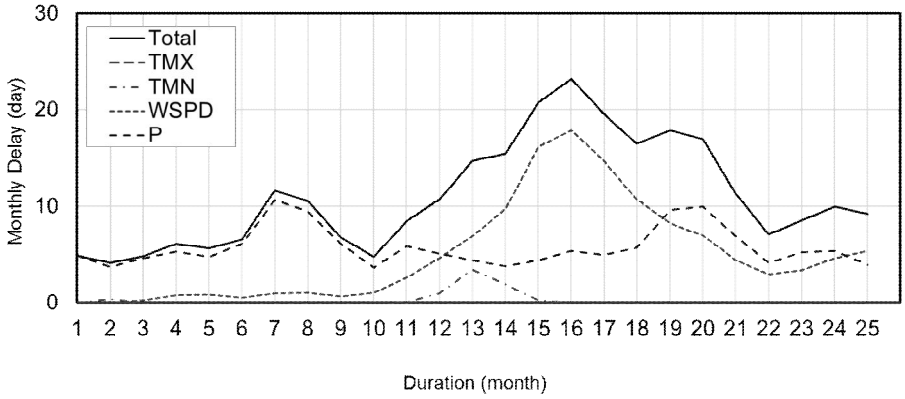


Figure 3-6 Time series of weather delay occurrence by types of weather variable

(b) Result 2-2: Relationship of Building Height and Severe Weather Effects

In the next step, a sensitivity analysis was carried out to examine the relationship between the height of the building construction and the effects of altitudinal variation in the weather delays. For this analysis, eight building construction cases were virtually set-up at 25-story intervals from 25 to 200 stories. These virtual cases consisted of the same work types and processes as those applied to the 50-story case above (Figure 3-5). As is shown in Fig-

ure 3-7, delays with and without the application of weather delays are simulated for the virtual cases. The results of the sensitivity analysis show that the proportion of the results without a vertical weather profile (ground-based in Figure 3-7) to those with the vertical weather profile (vertical-based in Figure 3-7) there is significant increase as the number of the story increases. That is, the degree of the mis-estimation of the weather delays without considering that the vertical weather profile can increase with the height of the buildings, especially in the case of a 200-story building which has 915.5-meter height, for which the latent weather delays will be at least twice the weather delays estimated using the existing method.

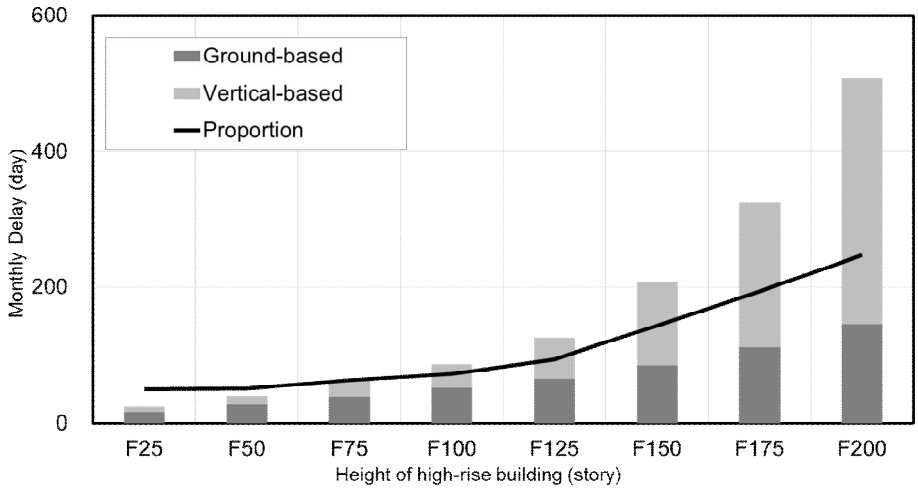


Figure 3-7 Sensitivity analysis for misestimated weather delay

3.6 Discussions

Construction processes are always exposed to various types of external influence factors, which occur independently of construction production system. These uncontrollable factors increase the variability in flows of construction processes and lead to construction delays directly affected by these factors and cost overruns due to unnecessary resources prepared for avoiding their negative effects. Severe weather is one of the most significant risk factors in construction processes, as they occur beyond the range of contractors' control and most construction projects are performed, exposed to the atmosphere. Hence, it is important to properly estimate their adverse effects on construction processes. Traditional ways for estimating non-working days owing to severe weather conditions are to calculate the average number of severe weather days that is possible to occur during an expected construction duration using 5-year historical weather data. This method is generally accepted in construction contracts in order to calculate compensable weather delay days. However, this method assumed that the numbers of adverse weather days and construction delay days are the same, because it considers that all construction works are identically affected by the severe weather event or the impact on a whole construction process can be explained by the relationship of specific types of construction works (i.e., works in critical path) and relevant weather factors.

However, in high-rise building construction, various types of construc-

tion works are performed concurrently in order to shorten an overall duration construction. In this case, the impact of severe weather on construction processes can be differ because there construction works have diverse characteristics according to type and are locally connected to each other. First, the type of material types, equipment, construction methods and the extent to be exposed to the atmosphere vary according to the type of construction works, which make it differ that the extent and type of weather variables affecting construction works. Moreover, in high-rise building constructions, the construction activities, even of the same work type, can be affected differently, because weather factors have characteristics to change with the increase of altitude and the altitude of working spaces of some construction activities are so high that weather conditions can be changed significantly at those working spaces. Second, different types of construction works that are carried out at intervals of several floors have a dependent relationship due to conflict of work space and equipment, however, the connectivity of construction activities is not global, but local. It means that the ripple effect of severe weather on a whole construction process is also restrictive, so that partial variation in a construction process may occur. For those reasons, the impact of severe weather on construction process may not be simply linear as calculated in the traditional methods.

Through simulation experiments, it is revealed that the number of monthly work stoppage days owing to adverse weather events does not show the seasonality. Weather variables generally show the seasonality that weath-

er events repeat with similar statistical properties in one-year intervals, as construction duration is not so long that climate changes occur. Hence, under the assumption of the traditional methods that severe weather days have the same number to that of construction delay days, non-working days have to show as the same seasonality as weather events do. However, in the simulation results, monthly days of weather delay as to precipitation repeats the pattern over a one-year period, while those as to other weather variables, (e.g., the daily minimum temperature and wind speed) do not show repetitive patterns. These non-seasonal patterns of weather delays days can be considered as the consequences of the heterogeneity of construction activities. In other words, it results from the composite effect of the followings: (1) weather factors that cause weather delays is different depending on the type of construction activities, (2) the duration of each construction work is different, and (3) the altitude, where construction activities are performed, is changed according to the progress of the construction process.

In addition, when work stoppages occur due to severe weather, the stopped activities is not all of the on-going activities, but only the parts of them, which relate to the weather variables causing the severe weather event. Therefore, not all of activity stoppages lead to delays of the overall construction duration. Construction delays are caused when construction activities in critical path are disrupted by severe weather. However, float times of construction activities are continuously changed owing to external influences so that critical path is not fixed but changeable. Particularly, as severe weather

events do not affect all construction activities uniformly and these activities have local dependence, float times of all construction activities are not identically changed, but partially changed. Hence, critical paths are dynamically changed during construction, and this can make it difficult to understand how severe weather events affect the states of construction activities and the construction duration. In this research, it was not examined how the critical path and the float times of construction activities are changed by the influence of severe weather events. Further studies on this will make it more explicit how a concurrent construction process is related to severe weather events.

This research attempted to examine the relationship of severe weather and construction processes whose components have heterogeneous characteristics and are locally connected to each other, as a result, it was revealed that the relationship between them is more complex than a simple linear relationship. Construction processes are constantly affected by uncontrollable external influence factors, which can have the direct impacts on a whole construction process. Even though these factors do not affect an overall construction duration, their local impacts on construction activities increase the variability in the supply process of material and equipment for these activities and can cause the secondary effect on a construction production system. On this account, the impact of external influence factors on construction production system may be possible to be explained not by simplifying dissimilar properties of construction activities and identifying the relationships

between those factors and a small number of the types of construction works, but by considering various characteristics and relationships of as many components as possible.

3.7 Summary

This study attempted to analyze what kind of impacts severe weathers make on concurrent construction processes, which is comprised of heterogeneous construction activities and of which activities are locally connected to each other. In this study, a simulation model was developed in order to propose a reasonable estimation method for weather delays in high-rise building construction, by integrating vertical weather profile generation models with the k-nearest neighbor resampling method and construction schedule simulation model with discrete event simulation methods. Using the proposed method, a case study with 50-story high-rise office building construction projects were carried out.

The results of the simulation experiments shows that: (1) a large difference can exists in the estimation of the effect of severe weather; (2) the pattern of weather delays in the application of the vertical weather profile does not exhibit annual cycles, especially in terms of wind speed; and (3) this difference can increase with the height of the building. The key findings of this research is that in concurrent constructions, which various construction work

types are performed simultaneously, the impact of external influence factors on the performances of construction production systems is so complex to be understood by the characteristics of their parts.

This study has made a practical contribution by proposing a simulation-based method for evaluating weather delays and their impacts on high-rise building construction. It also makes an academic contribution in analyzing the relationship between the weather condition and construction process, however, further study is necessary to clarify the additional questions such how the local impacts of severe weather events lead to construction durations and how their behaviors and relationship can be generalized.

Chapter 4. Interferences between Material Supply Processes Resulting from Sharing Supply Chain Resources

4.1 Introduction

High-rise building construction projects are large-scale projects, which have to supply a large amount of materials. However, due to their characteristics in site locations and product shape, it is difficult to secure a sufficient amount of supply chain resources such as yard storage and hoisting equipment. Hence, individual material supply processes cannot be allowed to have resources that each process can utilize independently, in many cases, they have to share resources without distinctions. Therefore, in the case that the capacity of the supply chain resources is excessively allocated to one process, the flows of other processes can be interfered with this. In order to minimize the interferences among the material supply processes sharing one resource, Just-In-Time (just-in-time) methods have been usually applied to such large-scale construction projects. Just-in-time is well-known as an effective method to minimize the interference of those processes by minimizing the amount of the inventory of individual processes.

However, just-in-time is a method not to control multiple processes as a whole by considering the interrelationship of them, but to control the indi-

vidual processes separately. Thus, even though just-in-time reduces the total inventory level, it cannot directly control the total inventory level and their variations during constructions, so that just-in-time cannot ensure that the total inventory level will not exceed the maximum capacity of the supply chain resources.

This research aims to examine these interferences among the material supply processes sharing the same type of the resources and their effect on construction production system. In order to achieve this goal, firstly, the material flow simulation model is developed which represents the material supply processes sharing insufficient resources and the interferences caused by those processes. In evaluating the impact of interferences on a construction process, the material flow simulation model is combined with an activity flow simulation model, which by extending the functions of the Construction Schedule Simulation model developed in the previous chapter. In the activity flow simulation model, activity agents will have the capability to autonomously determine their executions and performances considering material supply conditions. Secondly, simulation experiments are carried out to investigate interferences due to resource sharing as well as their effect on both construction and material supply processes

4.2 Material Production and Supply Method in Construction Project

High-rise buildings are made with a number of construction materials, so that construction supply chains are also comprised of a large number of suppliers and sub-contractors who supply those construction materials. When suppliers and sub-contractors produce and supply their products, there exist various types of production method that determine the start points of off-site material supply processes. To model off-site material supply process, it is important to define those production system of each type of materials

In manufacturing, it is important for suppliers to supply the right quantity of products and services to customers as soon as possible. In order to reduce a lead-time, it is the best way for supplier to select Make-To-Stock (MTS) production system, in which suppliers supply products that are produced in advance of customers' order (Ding et al. 2004; Stadtler 2008). The MTS production system does not require an additional time for production or assembly, so that they can supply stocked product immediately after orders are made. However, holing stocks for the MTS system causes corresponding inventory related costs, and if overstock can reduce the profit of suppliers. Therefore, MTS system should be based on the appropriate anticipation of demands of customers.

On the other hands, Make-to-Order (MTO) production systems aims to

make no stock and start to produce finished goods after customers' orders are made. The primary advantage of the MTO production system is to save the cost relating to holing stocks and to avoid the risk of an overstock that results from a wrong demand forecasting. On the other hand, the demand response time is usually longer than that of the MTS products (An & Fromm 2005). In consideration of the characteristics of products and services and the environment surrounding them, supplier and manufacturers select those production systems to increase their profit.

Construction market is a representative MTO system because in the most cases, contractors do not construct buildings and facilities until construction contracts are made with owners. When contracts between owners and contractors are made, owners generally provide information on buildings and facilities to contractors in the form of drawings and specifications. Based on the information, contractors make procurement plans and organize supply chains considering the production and supply capacity of suppliers and subcontractors. Accordingly, after this, the suppliers and subcontractors can be provided the information on how many and what type of construction material should be supplied to a construction site.

After construction supply chains are organized, suppliers and subcontractors are possible to predict the amount of construction materials they have to supply. Moreover, as their production capabilities on construction schedule are verified before participating to construction projects, if there are

no unexpected risk event in production, it can be considered that a sufficient time for production are given to them until the materials are used in construction sites. As the occurrence of unexpected risk events in material production are beyond the scope of this research, I assumes that the production processes of suppliers are not interrupted and production process are done without any problem until suppliers and sub-contractors have to supply materials to construction sites. Based on this assumption, all construction materials can be considered to be supplied in the MTS method that material supply processes starts with packing and shipping the materials whose production are done in advance. As a result, material orders that contractors make during construction is a request for suppliers and sun-contractors to transport their materials to construction sites.

4.3 Model Development

4.3.1 Entire Model Descriptions

Shown as Figure 4-1, the simulation model is comprised of two parts, off-site and on-site material flow models. The off-site material flow model represents the material flow from a material order by construction, packing materials, shipping material packages, and transporting packages to the construction site. In this model, materials in different work types are independent of each other. In addition, the on-site material flow model described ma-

terial delivery processes on building construction sites from entering transported material package, inspection, yard storing, and hoisting to working spaces.

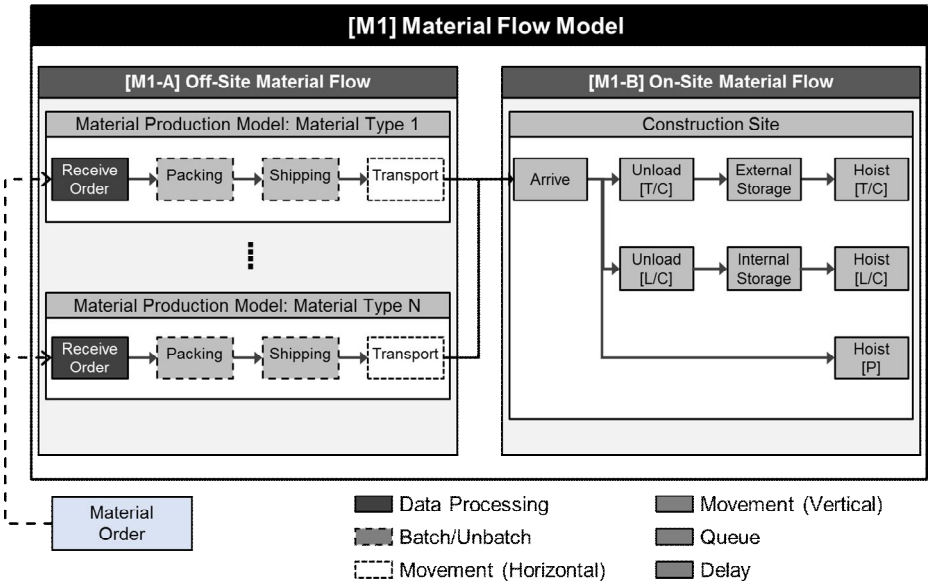


Figure 4-1 Conceptual model of material flow simulation model

4.3.2 Off-site Material Flow Model

As mentioned before, a high-rise building is constructed with large number of types of raw material and WIPs. And those construction materials are grouped by management units (e.g. sub-contractors, work types in Bill of Quantity) in order for efficient material management. The off-site material flow model is comprised of multiple material supply processes that represent a process of packing, shipping, and transporting materials from warehouses

of suppliers to a construction site. The process of the material production models begins with material orders from contractors and pre-produced material in stock start to be packed, shipped on suitable types of truck, and transported to the construction site.

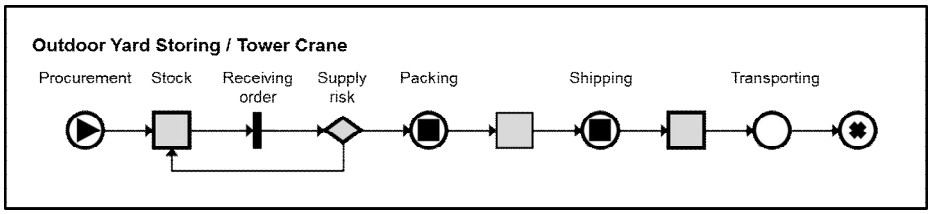


Figure 4-2 Process model of off-site material flow model

The process of the material production models begins with material orders from contractors and pre-produced material in stock start to be packed, shipped on suitable types of truck, and transported to the construction site.

As illustrated in Figure 4-2, the primary components of the material production models are as follows: (1) receiving material orders, (2) packing materials (3) shipping material packages on transportation equipment, and (4) transporting materials to the construction site. For calculating a delivery time of material packages to construction site, the equation of lead-time (L) is defined as follows:

$$L = t_w + \sum_i^p t_p^i + t_{tr} \tag{4-1}$$

where t_w is the time of waiting for shipping on a transportation vehicle; t_p^i is the time of shipping the i-th package on a transportation vehicle; N_p is the number of packages shipped in a transportation vehicle; and t_{tr} is the time of transportation from supplier's warehouse to a construction site.

(1) *Receiving material orders*: in this model, construction materials that are transported along the material flow process are entities that has information on the quantity of one type of materials for one construction activity. According to the assumption on the procurement of constructions, all material entities are created and stored as a stock before starting construction based on the schedule and bill of quantity for a construction project. The off-site process starts by receiving order information from a contractor on what types and how many materials should be delivered until day d. Among the various materials in inventory, materials that have the same type and quantity to order information is transferred from stock in inventory. Based on the probability variable that makes delivery failure, some of material entities which are randomly selected are delayed so that those material entities cannot be delivered that day.

(2) *Packing materials*: Through the previous step, the type and quantity of material are decided. As the information on the quantity of materials is based on Bill-of-Quantity (BOQ), the unit of quantity should be transformed as suitable to calculate the number of packages. For example, the amount of reinforcing bar is a ton in order, but for delivering materials, it matters how

many numbers of reinforcing bars will be packed. Thus, the amount of the ordered material is converted to the unit which has a deliverable form and is possible to measure the weight and size. Using the transfer rate of the ordered material, and the number of materials in unit package, the number of material package N_P to be calculated as the following equation:

$$N_p = \left\lceil Q_m^d \cdot U_m^{-1} \cdot P_m^{-1} \right\rceil \tag{4-2}$$

where Q_m^d is the quantity of the material type m that is to be delivered on the day d; U_m is the rate of transforming the unit of the material type m to the unit of package; and P_m is the quantity of the material type m that can be contained in one package.

(3) *Shipping material packages and selecting transportation equipment*: As the next step of the calculation of the number of packages, the type of transportation vehicles and the number of packages to be shipped are calculated. Firstly, in order to select transportation vehicles for giving a number of packages, the maximum weight and size loading bay of transportation vehicles are compared to the weight and size of material packages. The equation of the number of packages which can be shipped on the transportation vehicle type v is as follow:

$$N_{PIT}^{v,m} = \min\left(N_W^{v,m}, N_V^{v,m}\right) \tag{4-3}$$

$$N_W^{v,m} = \lfloor W_T^V / W_P^m \rfloor \tag{4-4}$$

$$N_V^{v,m} = \begin{cases} \lfloor L_T / L_P \rfloor \times \lfloor w_T / w_P \rfloor & (L_P > w_T) \\ \lfloor w_T / L_P \rfloor \times \lfloor L_T / w_P \rfloor & (L_P \le w_T) \end{cases} \tag{4-5}$$

where $N_{PIT}^{v,m}$ is the maximum number of packages of the material type m that can be loaded on the transportation vehicle type v; $N_W^{v,m}$ is the maximum number of packages of the material type m calculated by comparing the weight of the package to the shipping capacity of the transportation vehicle type v; $N_V^{v,m}$ i the maximum number of package of the material type m calculated by comparing the size (length and width) of the package to the shipping space of the transportation vehicle type v; W_T^v and W_P^m is the maximum capacity of the transportation vehicle type v and the weight of the package of the material type m; L_T and L_P is the length of the transportation vehicle type v and the package p; and w_T and w_P is the width of the transportation vehicle type v and the package p.

After calculating the number of packages by type of transportation vehicle, the number and type of transportation vehicles are calculated. To minimizing transportation cost, the number of transportation vehicles utilized for delivery should decrease by selecting vehicles as big as possible, but without empty space in the loading bay. Namely, in the case that the number of material packages is larger than the number of the loadable packages in the largest transportation vehicles, these largest vehicles are selected and material

packages are loaded. Then, if the rest of the package become smaller than those of the largest vehicle, the type of vehicles that is as small as possible to load those packages are selected.

The delay time and capacity for shipping material package vary depending on the type of construction materials and the circumstances of suppliers and subcontractors. The delay time for shipping don't have to be shorter than the time for unloading materials in the construction because even though the number of released transportation vehicles is excessively large, they have to wait to unload their package on yard storages and the waiting time of transportation vehicles causes additional cost for delay of unloading. Therefore, in this research, the time and capacity for shipping of suppliers and subcontractors are defined as not to be larger than time and capacity for unloading task of construction sites.

Transportation time are depending on the distance of warehouses of suppliers and sub-contractors and the traffic conditions at transporting time. In this study, it is assumed that the transportation time is independent of the traffic events that are dynamically changing and follows the normal distribution measured by the traffic data.

4.3.3 On-site Material Flows

Various types of construction materials that are delivered from the warehouses of suppliers and sub-contractors converge on a construction site. However, not all types of material packages are dealt with in the same way. As shown in Figure 4-3, there are three different types of on-site material delivery processes according to type of resources that have to be utilized for material delivery.

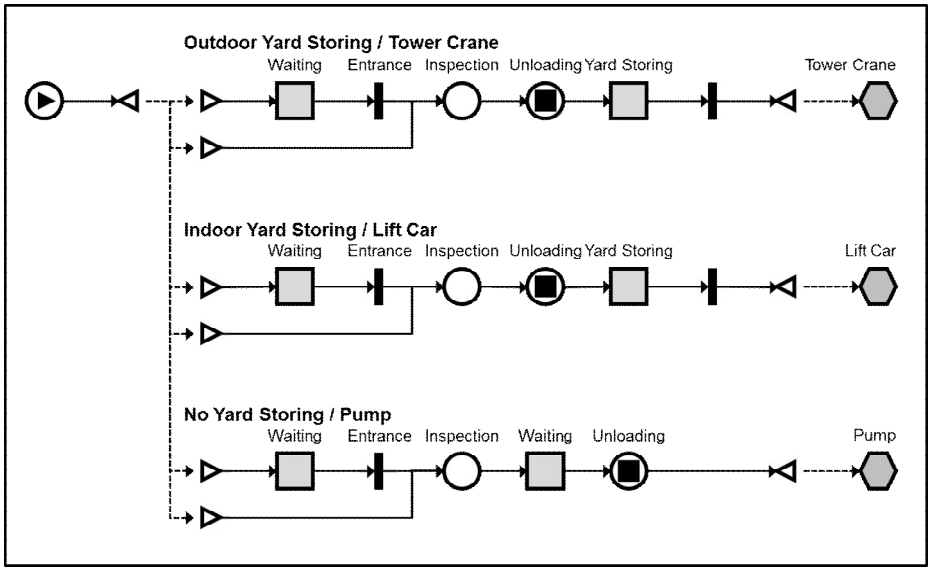


Figure 4-3 Process model of on-site material flow model

(1) *Outdoor yard storage / tower crane*: the materials that flow through the first group of the delivery processes utilize outdoor yard storages and tower cranes to be hoisted. The characteristics of these materials are as follows: (a)

materials are mainly related to structural works before construction lift cars are installed so that other hoisting equipment cannot be used, (b) the volume and weight of materials are so large to be hoisted using other hoisting equipment, and (c) the materials are seldom damaged by external weather conditions. The materials such as reinforced bar, structural steel beams, and deck plate is included in this group.

Figure 4-4 Picture of construction site of high-rise building construction project in Korea

(2) *Indoor yard storage / lift-car*: the next group of the delivery processes utilizes indoor yard storage and lift cars inside of buildings. The characteristics of these materials that is delivered through this process are as follows: (a) materials are mainly related to interior works after finishing curtain-wall works so that material cannot be hoisted with tower crane, (b) the volume and weight of materials are relatively small, and (c) the materials can be damaged by external weather conditions. The materials such as finishing materials, floor materials and furniture belong to this group.

(3) *No yard storage / pump-car*: the final group of the delivery processes does not use the yard storage space and hoisted with pump car as soon as materials are entered into construction sites. Only the type of material delivered through this process is ready-mixed concrete.

Each on-site material delivery process is comprised of several steps: (1) Arrival and Entrance of Transportation Vehicles; (2) Yard Storages and Calculation of Inventory Level; and (3) Vertical Transportation with Hoisting Equipment. Due to the difference of resources utilized for material delivery, some steps can be skipped in on-site material delivery processes.

(1) *Arrival and Entrance of Transportation Vehicles*: as shown in Figure 4-4, the construction site of high-rise building construction is significantly congested with the small space for material delivery that transportation vehicles that arrive at construction sites cannot enter into the site for the next delivery

process and lined up outside of the entrances to the site. For transportation vehicles to enter into a construction site, the following conditions should be satisfied: (a) there is no other transportation vehicle that is approaching yard storages and is unloading material packages in the same type of the delivery process, and (b) inventory level should not exceed the capacity of yard storage. The entering order of transportation vehicles is basically based on the First-In-First-Out methods.

(2) *Yard Storages and Calculation of Inventory Level*: after transportation vehicles are allowed to pass through to the entrance of the construction site, two inspections and unload process is followed as illustrated in Figure 4-3. The inspection process is to check the type, quantity and quality of the transported materials and the unloading process is to unload material package from the transportation vehicles. In this study, the times for inspecting and unloading a material package are assumed as that they are identically dealt with to all types of materials. After material packages are unloaded, they are added in yard storages and the inventory level of the storages is also changing. For calculating the inventory level, the following assumptions are made as: (a) the shape of material packages are not considered so that the area of the floor surface of the material package is the primary element for the calculation, (b) interval between material package are expressed using the weighted value w_{intv} which is identically applied to all types of material packages, and (c) the same type of materials are stored in the space place and they are grouped as a new package without packages that are not fully load-

ed. The equation of the inventory level IL is as follow:

$$IL = \sum_{m}^{N_m} \left\lceil Q_{(m)} \cdot U_{(m)}^{-1} \cdot P_{(m)}^{-1} \right\rceil \cdot PW_{(m)} \cdot PL_{(m)} \cdot w_{intv} \tag{4-6}$$

where N_m is the number of the material type m which is stored in the yard storage; Q_m is the quantity of the material type m; U_m is the rate of transforming the unit of the material type m to the unit of package; and P_m is the quantity of the material type m that can be contained in one package; $PW_{(m)}$ is the width of the package of the material type m; $PL_{(m)}$ is the length of the package of the material type m; and w_{intv} is the weight to compensating the loss of the yard storage space due to the interval space among material packages. As ready-mixed concrete does not have to be stored in those yard storages, the unloading process equals in the hoisting process using the pumping cars.

(3) *Vertical Transportation with Hoisting Equipment*: In order to transport the construction materials from the yard storage to the working floor at height, three types of hoisting equipment are utilized in the high-rise building construction site: (a) tower cranes, (b) lift cars, and (c) concrete pumps. The selection of type of hoisting equipment for construction materials is determined by physical characteristics (transportable weight and volume), the usability of hoisting equipment, and so on.

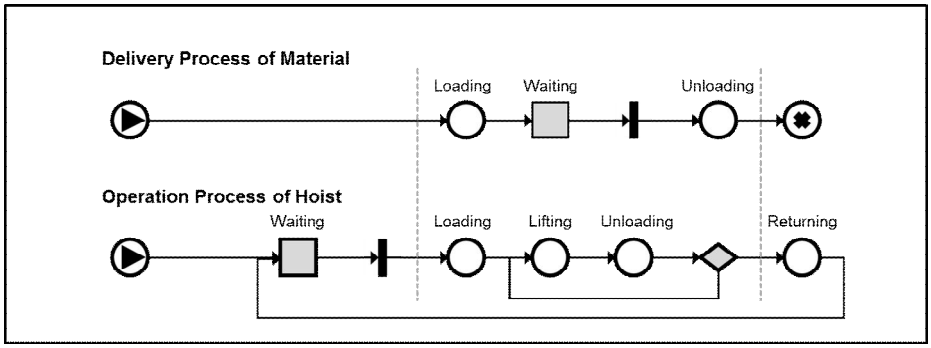


Figure 4-5 Process model of hoisting operation and material transportation

Hoisting processes vary depending on the type of hoisting equipment. For example, a lifting process of tower cranes can be defined as a series of elements such as material tie/untie, hoist motion, trolley motion, holding time, returning. Moreover, the lifting process of lift cars is defined by the different elements to those of tower cranes such as door open/close, material loading/unloading, lifting, and returning. The lifting process of concrete pump has simpler process, comparing to other types of equipment for this type of equipment do not have to return back to yard storage space to load the next materials. Even though those processes of hoisting equipment consist of the different elements, hoisting processes can be simplified with common elements shown in Figure 4-5: (a) loading materials, (b) lifting to the destination space (c) unloading materials, and (d) returning to yard storage. The equation of cycle time of hoisting task (T_{cycle}) is defined as follows:

$$T_{cycle} = t_l + \sum_i^d \left(t_L^i + t_u \right) + t_r \tag{4-7}$$

where t_l is the time of loading materials; d is the number of the destination floors in one lifting cycle; t_L^i is the delay time for lifting materials in the i-th travel in one cycle; t_u is the time of unloading materials; and t_r is the time of returning to the yard storage on the ground level. The time variables of loading (t_l) and unloading (t_u) materials are various depending on equipment type and they have to be defined differently considering the characteristics of hoisting equipment type and specification. However, in this study, these variables are assumed that they are independent of type of materials. Therefore, if the type of hoisting equipment is same, the delay times are identically calculated based on a random selection using probability distribution, uniform distribution, and independent of the type of construction materials.

Whereas, the time variables of lifting (t_L) and returning (t_r) can be largely variable depending on traveling distance since the height of high-rise building is tall enough to remarkably influence the lifting and returning time. The lifting time t_L is defined as:

$$t_L = t_{vm} + t_{hm} + t_h \tag{4-8}$$

$$t_{vm} = V^e \cdot D^{-1} \quad (D = \sum_{f=f_a}^{f_d-1} h_{floor}^f) \tag{4-9}$$

where T_{vm} and T_{hm} are the times of the vertical and horizontal movement; V_e is the average lifting speed of the equipment type e; D is the lifting distance between the floor f_a and the floor f_d; and h_{floor}^f is the floor height of the floor f.

4.3.4 Integration with Activity Flow Simulation Models

In the real world, processes in construction projects do not continue their operation throughout the day and include various time events such as start, break, resume, and finish. However, process in a simulation model do not have to represent all those time events using a 24-hour clock as the processes of the real world do. Under the assumption that non-working period (e.g., break time, an after-work time) do not make any effect on their processes; a simulation model can employ the time clock as their working hours. This method enables process to continue without any break, so that a model can simulate these processes in a simplified way.

However, in the case to integrate two simulation models with the different time concept, this method cause a problem. For instance, in high-rise building constructions, an early-morning and night work are essential to supply a large amount of materials, while construction works determines the start and finish time in the light of situations of individual participants. The discrepancy of time concepts can creates a wrong information exchange by changing the order of event occurrence when they are interacting with each other. Because the results of a simulation model are very sensitive to the cumulative effect of repetitive calculations with wrong data, it is very important to apply the same time clock to all simulation models. In this research, a 24-hour time clock is employed and the different time concepts of the activity and material flow simulation models are integrated as illustrated

in Figure 4-6. Instead, the time events that have to be reflected in each model are as follows.

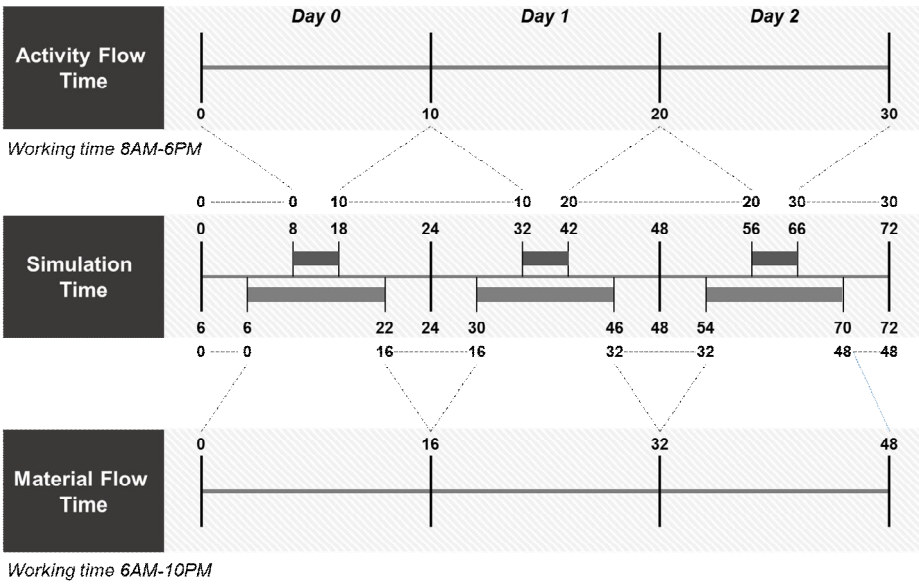


Figure 4-6 Time-synchronization of activity flow model and material flow model

(1) *The material flow simulation model*: the material flow model consists of two different types of models, the off-site and on-site material flow models. The start and finish times of the two models have to be set up differently because transportation vehicles departing from the off-site material flow model cannot arrive at construction site when the on-site model is out of its operation. Therefore, the off-site model start and finish their process earlier than the on-site model

(2) *The activity flow simulation model*: in this research, it is assumed that all construction activities are performed within the common working hour. Therefore, all activity agents pause and resume their daily operations at the same time. In addition, the construction process is performed along the schedule calendar including various types of non-working days. Therefore, on non-working days, all construction activities do not start, but this schedule is not related to material supply process. In order to reflect those events to the activity flow simulation model, the behavior rules of activity agents are revised as shown in Figure 4-7.

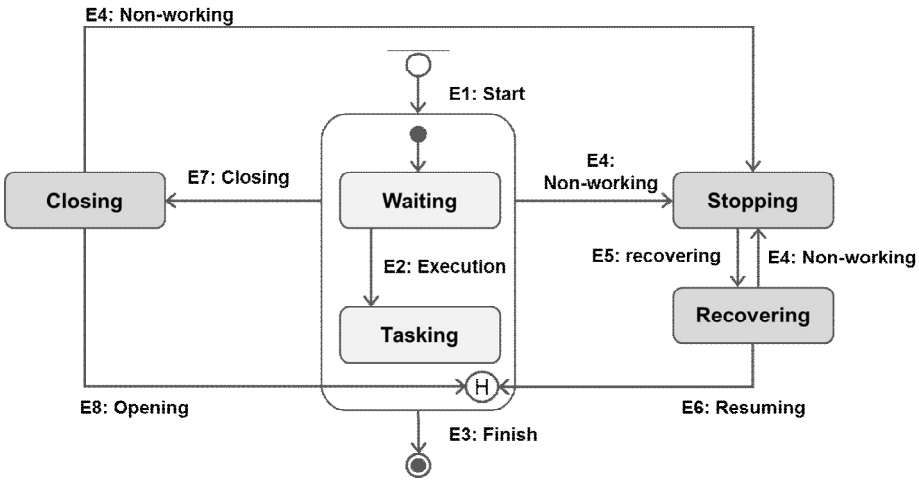


Figure 4-7 State chart of activity agents in activity flow simulation model

4.4 Simulation Experiments and Results

4.4.1 Input Data Descriptions

To conduct simulation experiments, the data measured from a real high-rise building construction project are applied to the developed simulation model. The case is a high-rise office building construction project located in Seoul, Korea, which is comprised of one high-rise office building with 50 stories and one auditorium building with four stories. The auditorium building is on the same project site but separated from the office building so that this building is excluded from the case study with the assumption that construction and material supply processes of the auditorium building construction don't have any effect on those of the high-rise building construction.

The range of construction data of the office building are used from the 6th floor to the 47th floors because the floors from the 1st ~ 5th floor had been used as a site office during construction and construction works for those floors is performed on the last stage of construction schedule. The construction schedule is illustrated in Figure 4-8. The construction materials used in the case includes 266 items among the total of 550 items that were used in structural work and interior works and the materials of Mechanical, Electrical, and Plumbing (MEP) works are excluded. The delivery of all construction materials is scheduled to be arriving at the construction site the day before the related construction activities are executed.

The transportation vehicles used for material transportation varies depending on the suppliers and subcontractors, but here, it is assumed that the transportation of construction materials in the off-site material flow models are conducted using the eight types of transportation vehicles which have standardized specifications for construction materials transportation as shown in Table 4-1. For the supply chain resources in the on-site material flow models, the areas of the outdoor and indoor yard storages is 1424 m^2 and 622 m^2, respectively, and the number and specification of hoisting equipment are illustrated in Table 4-2.

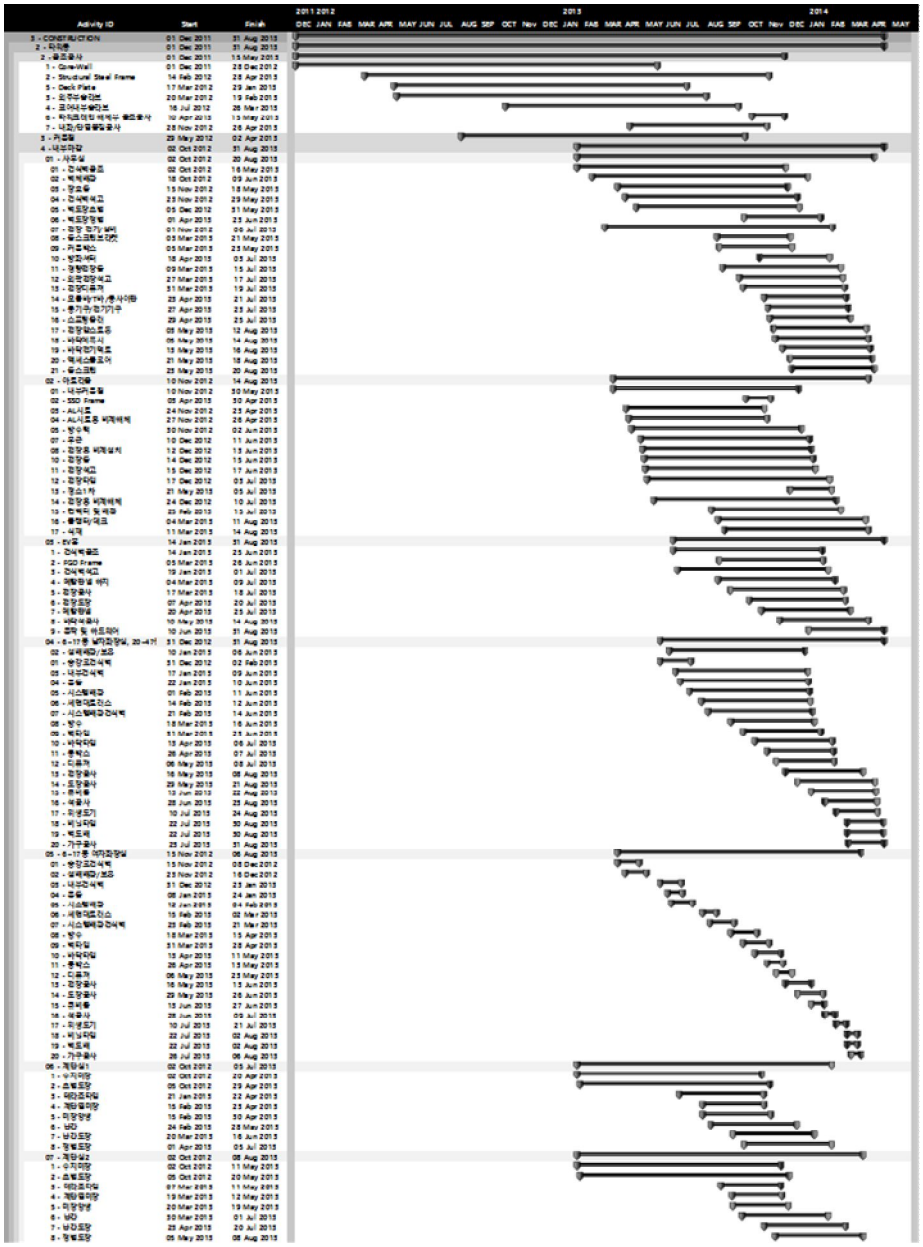


Figure 4-8 Schedule table of high-rise building construction for case study

Table 4-1 Type and specification of transportation vehicles

Type	Weight (kg)	Length (m)	Width (m)
T1000	1000	2800	1600
T1400	1400	3100	1700
T2500	2500	4300	1800
T3500	3500	4600	2050
T5000	5000	8000	2300
T11000	11000	9100	2500
T25000	25000	9100	2500
TR27000	27000	13300	2750

Table 4-2 Type and specification of Hoisting Equipment

Type	ID	Number	Lifting Speed (M/Min)	Time Loading (Min)	Time Unloading (Min)	Time MoveH1 (Min)	Time MoveH2 (Min)
TC	CTL400	2	60	10	20	1	1
LC	SS-2545T	2	100	3	3	0	0
LC	SS-2547S	1	80	3	3	0	0
LC	MS-1528S	1	60	3	3	0	0

4.4.2 Experiment Descriptions

Using the developed material flow simulation model, the simulation ex-

periment is conducted to examine: (1) the interferences between material supply processes in different types, and (2) the influence of the interference of material supply processes on the construction performance.

4.4.3 Simulation Results

Analysis 1: Occurrence of Interference of Material Supply Process and Variation of Inventory Level

In order to confirm the complex behavior that results from the sharing of the limited supply chain resource, temporal changes of the relevant parameters during simulation is investigated.

(a) Result 1-1: Variation of the Inventory Level of Yard Storage

Firstly, the variation of the inventory level of the outdoor yard storage and the indoor yard storage was analyzed as shown in Figure 4-9. The patterns of the inventory level of the yard storages show the irregular and non-repetitive both in the outdoor and indoor yard storage. The inventory level of the outdoor yard storage, which is related to materials for structural works, is relatively repetitively patterns comparing to those of the indoor yard storage, however, the variability of the patterns is larger. The materials for structural works include a small number of material types and the inventory level is greatly dependent on a few number of material types such as mega-column

and beam. On the other hands, the inventory level of the indoor yard storage, which is related to interior works, is greatly fluctuated.

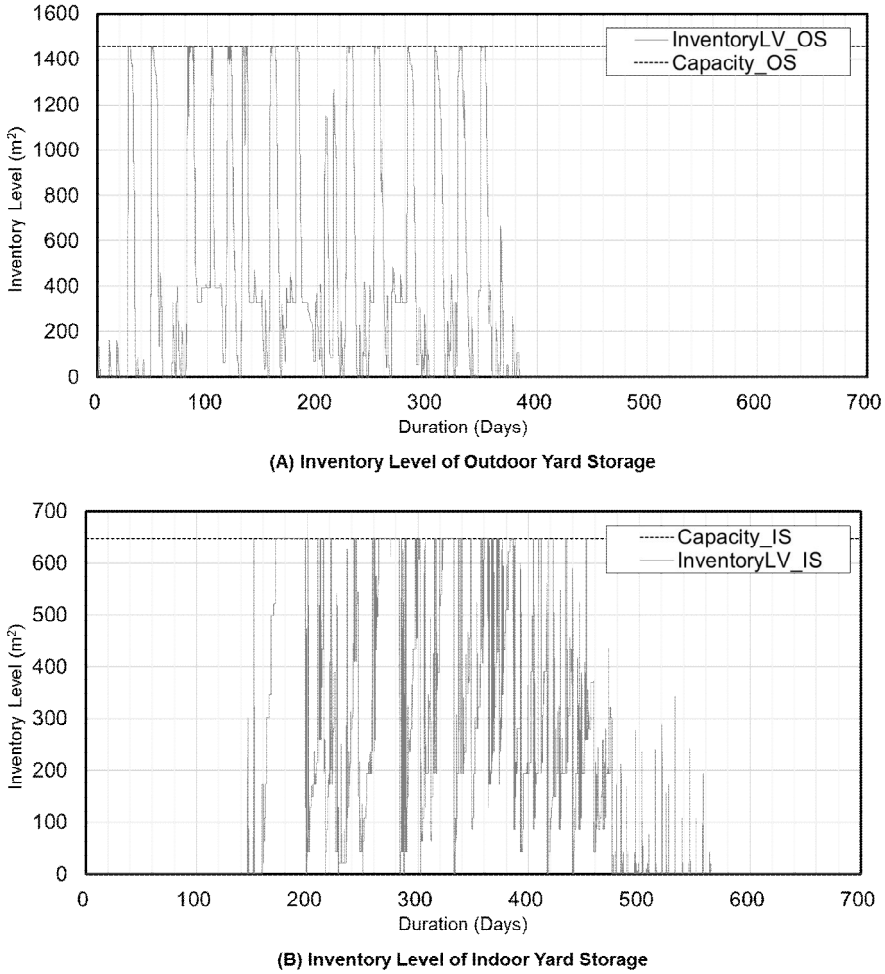


Figure 4-9 Dynamic change of inventory level of outdoor yard storage (A) and indoor yard storage (B) during construction

In other words, when construction managers make inventory planning for one type of construction materials, the available yard storing space for

the supply of this material is difficult to be calculated due to the great fluctuation. Traditional inventory management methods such as Economic Order Quantity is based on the assumption that the capacity of storage for one type of construction material is constant and it is independent of inventory management for other type of materials.

(b) Result 1-2: Delays due to Limited Resources

Secondly, in order to confirm the occurrence of delivery delays due to limited supply chain sources, the delivery time of construction materials is measured in regard to the times when they are ordered, transported to the construction site, and stored in yard storage. Figure 4-10 shows the cumulated quantity of reinforcing bar (rebar). The Q_dmat_ordered (black line), Q_dmat_stored (gray line), and Q_dmat_tranported (dot black line) in Figure 4-10 indicate the cumulated quantity of rebar ordered, transported to construction site, and stored in the yard storage, respectively. Material transportation begins immediately after delivery orders are made, but the large amount of delays appeared in the process of the deliveries. In consideration that all the materials are planned as delivered until the day before construction activities are executed, the time delays more than one day may cause schedule delays. In the rebar transportations, the failures of the delivery on time are observed, due to the lack of the outdoor yard storage space that is shared by other types of construction materials.

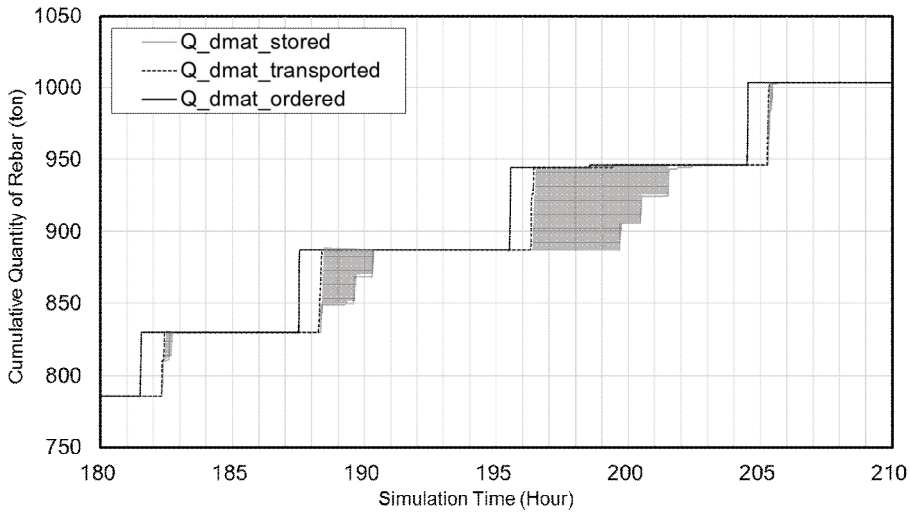


Figure 4-10 Occurrence of delays in material supply process due to limited yard storage space

(c) Result 1-3: Interferences among Material Supply Processes

In addition, the interference in occupying the limited resources between the supply process of distinct material type is analyzed. Figure 4-11 illustrated the sample data the temporal variation of the inventory level of one material type of deck plates (black line) and the available storage capacity from the perspective of the inventory management of deck plates (gray line). Namely, the available yard storage capacity is calculated as the difference of empty space in the yard storage and the inventory level of the deck plates. Accordingly, the meeting point of two lines means that the inventory level of the storage is full and the supply materials are stopped until the inventory level is reduced. Since the interference between different material types occurs in the condition that there is no available space for

stocking additional materials.

As shown in Figure 4-11, the several points where the conflicts can occur (dotted gray circle and rantagle) are found during construction and the direction of interference can be provisionally identified considering the pattern of the inventory level of deck plates and the available storage capacity. The dotted gray circles are the points where the inventory level of deck plates are constant and the rapidly growing inventory level of other materials is interrupted, therefore it can be considered as the case that the stocks of deck plates make the interference in allocating the storage space to other types of material. And, the dotted gray rectangles are the points where the storage space is fully occupied by other types of materials and the inventory level of deck plates increase right after the available storage capacity is recovered. This pattern can be interpreted as the interuption that the supply of deck plates is delayed by other materials. Finally, the dotted gray hexagon is the point where the inventory levels of the deck plates and the other types simultaneously increase, so both material types influence the supply processes of each other.

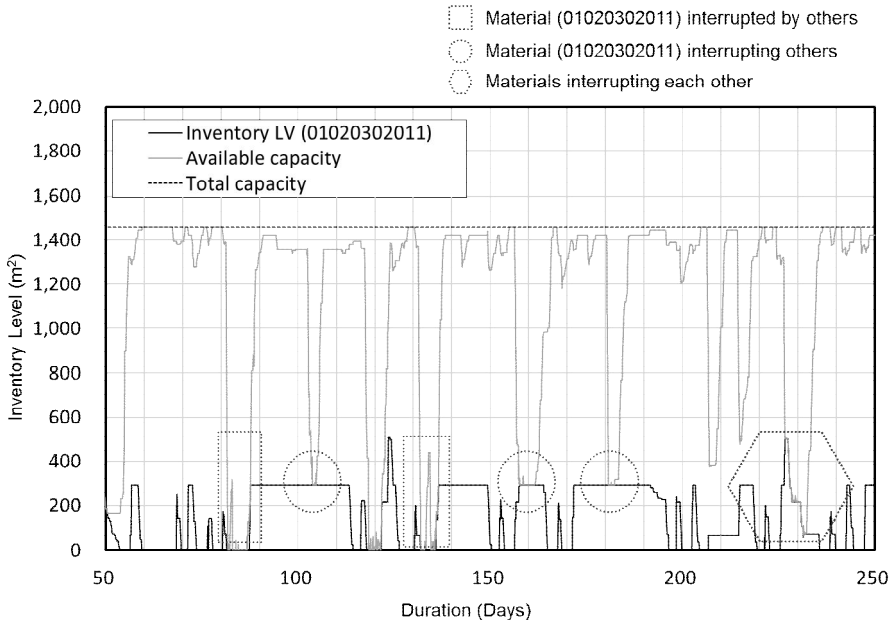


Figure 4-11 Interferences in occupying yard storage space between materials

Analysis 2: Impact of Interference of Material Supply Processes on Construction Supply Chain

For the next step of the analyses, sensitivity analysis are carried out in order to examine the impact of supply chain resource on the performance of construction project under the condition that the resource is shared by various types of materials. The capacities of yard storages are controlled and the overall duration and lead-time are measured. The number of simulation runs for a specific condition is set up as 100 times and the average values are calculated.

(a) Result 2-1: Impact of Interference on Construction Schedule

Firstly, the variation of the overall project duration according to the capacity of the yard storages are analyzed. The chart as shown in Figure 4-12 means the number of finished construction activities during construction by storage capacity. The project duration increases with the decrease of the capacity of yard storages, however, the increase rate of the project duration is not constant and over the specific level of capacity, the effect on the duration is not shown. Moreover, the sections where project delays occur are not uniformly distributed during construction, and according to the capacity of yard storages, the simulation cases that is affected and not affected by resource conditions are distinctively divided. For example, the period between 150 and 250 days, the simulation cases that have the capacity less than 50% are delayed, while the others are not influenced. In addition, the period between 250 and 350 days, the schedule progress of the simulation cases with less capacity than 40% capacity are diverged.

Those irregular occurrences of schedule delays are considered as the composite effect of the shortage of storing space for materials and the delays of the relevant activities suing those delayed materials and in the critical path. The cumulative effect of delays of non-critical activities also can cause the change of critical path. For such reasons, the supply processes and construction activities are interconnected complicatedly, and it is difficult to analytically examine the occurrence of negative effect of the limited resources.

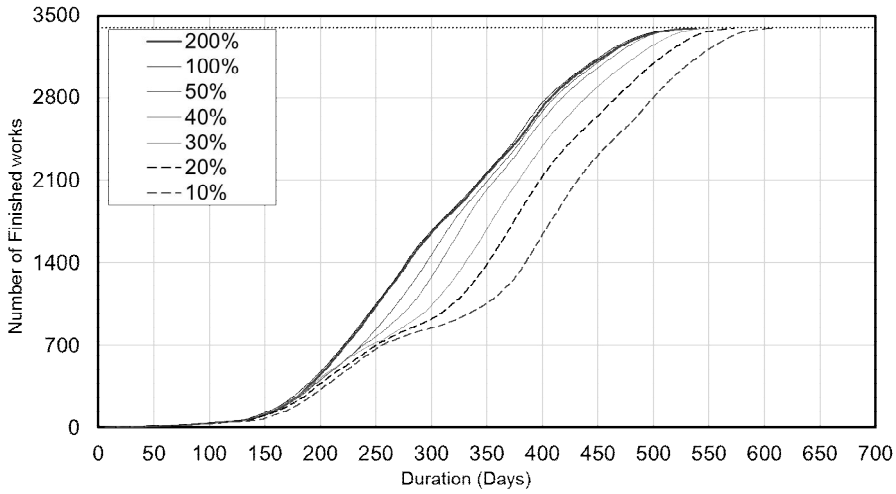


Figure 4-12 Variation of overall duration of construction project by capacity of yard storage

(b) Result 2-2: Impact of Interference on Material Supply Process

For the next step, the transportation time is measured with the variation of the capacity of the yard storage space. The chart in Figure 4-13 shows the discrete probability distribution of the waiting time of transportation vehicles from the arrival at the construction site to the entering into the site. The probability of them exponentially decrease as the time increases and the patterns of them shows the similarity to those of the exponential distribution. From the assumption that all materials are delivered to the construction site the day before the relevant construction activities are executed, the transportation times that are larger than two days can cause the activity delays. In addition, in the case that the arrived transportation vehicles cannot enter the site and unload their material packages in a given time, the additional cost

for transportation vehicles is to be incurred. If the transportation time is longer than 2 days owing to the congested storage, the material packages that cannot be unloaded have to be transferred to external temporary storages and moved back to the site after the storage space become available. It leads to both transportation cost and rental cost additionally.

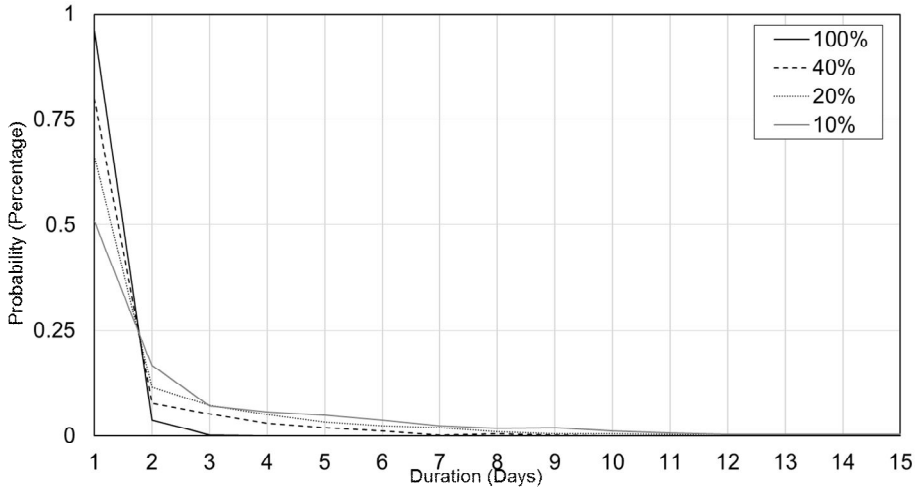


Figure 4-13 Waiting time of transportation vehicles to enter sites due to lack of capacity of yard storage

4.5 Discussions

When construction managers control the multiple number of processes, it is essential to separately assign resources in order to reduce the variability caused by the interference between those processes. However, in many cases of construction production systems, different types of processes have to

share resources due to insufficient provision or efficient utilization. In high-rise building construction project, there are many cases that resources for material supply processes (e.g., yard storage, hoisting equipment) cannot be installed sufficiently, therefore, their resources are shared by different types of material supply processes without distinction, and this makes it difficult to appropriately make a plan and control these processes. Traditional methods for material supply and inventory management separately determine the inventory levels of individual material types with no regard to their interference. For example, in Economic Order Quantity (EOQ) method, the order quantity and safety inventory level of each type of materials in consideration of lead time, demand rate, and resource capacity of that type of materials. This method is useful to find the order quantity and a safety inventory level to minimize the cost of material supply. However, under the conditions that the interference with the other material supply process occur due to lack of resources, it is difficult to ensure the minimized cost, because the planned inventory level and material supply quantity can be interfered by the inventory of other types of materials.

In order to overcome this disadvantage of those methods, just-in-time method are applied in construction sites, where resources are limited. By minimizing the inventory level of each type of materials, just-in-time minimizes the interference between different types of material supply processes. However, recent literature mentioned that the way to minimize the inventory level is not always effective because keeping a small inventory level is vul-

nerable to the variability of material supply. Just-in-time is effective to minimize the inventory level of each type of construction materials with regard to its demand, but this method does not suggest the way to minimize the total inventory level as a collective result of all material types of construction materials. Hence, taken as a whole, the excessive inventory (i.e., the shortage of resource capacity) and delays of material supply can occur even in just-in-time application.

In this chapter, the simulation model is developed, which represents the material supply processes that share the yard storage space and hoisting equipment based on the just-in-time material management method. In addition, simulation experiments were carried out to investigating the effect of resource sharing. First, by analyzing the inventory level of the yard storage spaces, it was clarified that the total inventory level is so high fluctuated irregularly and the interference between construction supply processes occurs in the various forms. Even though it is not verified through a statistical analysis, in this simulation experiments, the inventory level of the outside yard storage, where a smaller number of heavy-weight materials (e.g., structural steel frames) are stored, shows less fluctuation than that of the inside yard storage, where a larger number of light-weight materials (e.g., finishing materials) are stored.

In addition, through the simulation results, it is demonstrated that the interferences in the yard storage cause an adverse effect on the construction

process and increase supply cost by delaying lead-time. Delays of material supply can negatively affect construction activities related to delayed materials, then these affected activities also affect the predecessor activities and material supply processes of these activities. In other words, as construction and material supply process comprise a feedback system, the interference occurring in yard storage has the possibility to increase the variability in a whole process, which makes it difficult to estimate the fluctuation of the inventory level of the yard storages as well as the occurrence patterns of interferences.

This research clarified that in the case that multiple processes have to share resources, just-in-time is effective method can reduce a total inventory level by minimizing the inventory levels of individual processes; however, in this case, just-in-time is not a method that ensures to prevent the interferences that happen because the total inventory exceeds the resource capacity. The interferences between processes show irregular patterns and is able to cause a negative effect on production systems by increasing the variability. To appropriately control the inventory level and prevent the interference between processes, it will be necessary to apply a more comprehensive method that analyzes the variation of the total inventory level in the holistic perspective. Hence, a future research will focus on controlling the total inventory level, which is difficult to estimate its pattern due to complex behaviors of construction production systems.

4.6 Summary

This study was conducted to examine the interference occurring in the case that dissimilar types of material supply processes have to share insufficient resources. The material flow simulation model was developed to represent the interactive behaviors between different types of material processes owing to the sharing of the limited resources and the influence of the interactive behaviors on construction projects. In addition, in order to examine their impact on construction processes, the material flow simulation model was integrated into the activity flow simulation model developed by expanding the functions of the construction process simulation model of the Chapter 3. Using this model, simulation experiments were carried out based on real data of a high-rise building construction project.

Though the simulation experiments, the inventory level in yard storages that are shared by a large number of material supply process is so fluctuated and changed with irregular patterns. In addition, the interferences that occur due to the excessive increase of the total inventory level have a negative effect on material supply processes as well as construction processes. Therefore, in the case that a number of processes have to share insufficient resource capacity to handle the inventories of those processes, the existing inventory management methods, which separately control individual processes, are necessary for reducing the interference, but insufficient to control a whole process. Hence, the way to consider not only the characteristics of

individual processes, but also the interrelationship of processes is necessary to understand complex behaviors of construction production systems and increase their performance.

The modeling method proposed in this research can be applied for analyzing the patterns of the inventory level and the occurrence of the interferences resulting from the lack of supply chain resources. However, this method has the limitation to minimize the negative effect of the interferences by properly allocating resources to processes. Therefore, further research will focus on the allocation methods to maximize the performance of construction production systems that suffers from the insufficiency of resource capacity.

Chapter 5. Spatial Conflicts between Construction and Material Supply Processes in Allocating Internal Workspace

5.1 Introduction

In management of supply chains, generally, it is not considered that a construction process has a negative effect on material supply process. In the perspective of flow, if construction activities are stopped, the relevant material supply processes are also stopped for as much time as the activities are stopped.

In high-rise building constructions, a limited yard storage space makes construction materials to be transferred to workspace in the building as soon as possible in order to avoid congestions of yard storage space. However, it is a problem not only that the internal spaces of buildings are insufficient to store all construction materials (Riley and Sanvido 1997; Said and El-Rayes 2013), but also that the available area of the spaces is changed by construction works (Riley and Sanvido 1995), because they requires a certain space for performing works and the structure, shape and states of these spaces are changed as a result of construction works. Lack of storage spaces inside of buildings has the possibility to incur spatial conflicts between construction and material supply process, which could affect a construction process be-

cause both construction and material supply processes are comprised of interrelated components.

Thus, this research is conducted with the purpose of examining the occurrence of conflicts between construction and material supply processes due to lack of space and their effects on both processes. To do this, first, I develop a simulation model that represents the process that the internal spaces of buildings are occupied by those two processes, as well as the process that the states of these spaces are changed according to the progress of a process construction. Based on the agent-based modeling, a space agent model is developed to be able to control demands for space usage by two processes, then the simulation models as to construction and material supply process (developed in Chapter 3 and 4) are combined in this model. Second, simulation experiments with real data of a high-rise building construction are conducted in order to examine the spatial conflicts and their effects on the supply chains of building construction projects.

5.2 Space Conflicts in Building Constructions

5.2.1 Space Hierarchical Structure in Building Construction

In building constructions, space is a concept to be utilized for both construction works and material supply work. As the purposes of construction

and material supply are different, space is also differently defined and have different ranges in the activity flow and material flow.

(1) *Space in the material flow*: in the material flow, the definition of space is the destination where construction materials have to be transported and installed. The destination information of materials is included in the bill of quantity (BOQ) that contains information on what type and how many materials are needed in which place. Therefore, the definition of space in the material flow is based on the calculation unit of quantity take-off, and a room is used as a unit for quantity take-off.

(2) *Space in the activity flow*: in the activity flow, space means work spaces utilized by construction crews. Workspace is an abstractive concept and defined by construction managers who divide a building into multiple sections in order to make the construction schedule and plans controllable and easy to understand. Therefore, the spaces in construction schedules do not concern with the spaces that are defined for the material flow and can choose a broader range of space than that of the material flow, for example, including multiple rooms and one higher level of space such as floor and zone.

In a production process in manufacturing, material supply and production processes share the identical definition and classification of spaces. Therefore, the availability of space can be determined in a simple method to

confirm the condition of the required space. On the other hand, in the construction process, the definition and classification of space are different between material supply and production processes, depending on type of construction plans (Thabet and Beliveau 1994; Guo 2002). Therefore, in order to identify spatial conflicts among construction processes and material supply processes and check the availability of space for a specific activity, the definition of space employed by those two processes should be made to eliminate the conceptual gaps.

To solve this problem, a space hierarchical structure with five levels is defined considering both bill of quantities and schedule table of building constructions. Shown as Figure 5-1, the highest level of the hierarchical structure is a building that is the final purpose of construction projects and the lowest level of the structure is a room which is based on space unit for quantity take-offs. Other levels between the highest and lowest level are defined using a space unit used in the schedule table. Space of higher level should include an entire area of space on lower level that is included in the higher level. Using this hierarchical structure, the space conflicts caused by material supply and construction can be expressed even though those processes utilize different concepts and ranges of space. For example, in the case that the space is occupied by a construction worker, spaces of the lower level that are included in that space are also occupied by the construction work, storing materials or other construction activities are prohibited until if the space-occupying activity does not allow the sharing of space for other

activities.

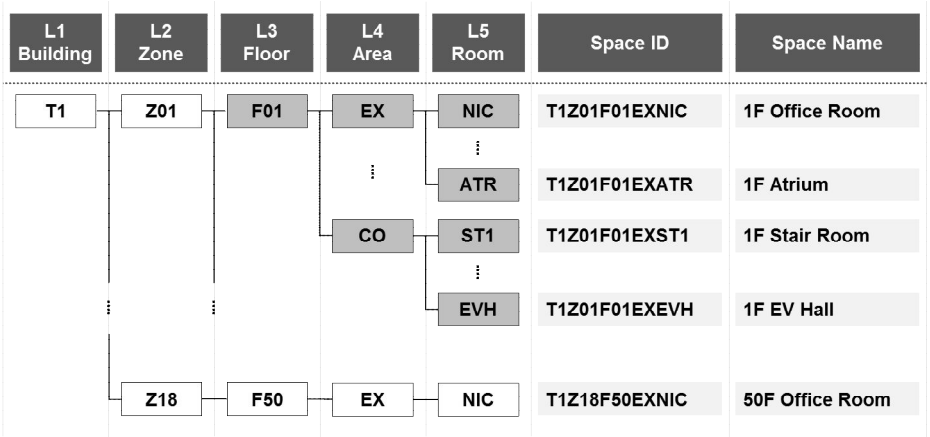


Figure 5-1 Examples of level-5 hierarchical structure of building space

5.2.2 Types of Spatial Conflicts between Workspace and Material Storage Space

Due to the conflicts between working spaces and material storing spaces, the materials in the yard storages can be interrupted to be transported to the next location. Therefore, it is important to identify type of spatial conflicts in building spaces. There are two types of conflicts between activity process and material storing process: (1) space creation condition; and (2) space occupancy condition.

(1) *Space creation condition*

As building spaces can be regard as WIPs and final products resulting from construction activities, the states of the building spaces are changed according to the progress of the construction process (Thabet and Beliveau 1997). Moreover, some states of spaces cannot perform a role in storing supplied materials. For example, before or during structural works, materials that is not relevant to those works cannot be transferred to these spaces because there is no space physically holding up them. Those states of space are directly connected to activity progress so that delays of activities can make materials that is already delivered to construction sites unable to be hoisted to working spaces.

For representing this type of conflicts in the model, the concept of space creation state is devised. Some types of construction activities that create a significant spatial change such as structural steel framework works, concrete placement works and masonry works have their own integer code that distinguishes states of them to other types of construction activities. According to a schedule process, predecessor activities in the schedule are assigned lower integer codes, on the contrary, successor activities are assigned higher integer codes. When construction activities that are assigned space creation codes are finished, the spaces that those activities are performed assigned the state space creation code of those activities. Therefore, construction materials can be transferred to the inside of buildings only in the case that the des-

tination space has bigger codes than those of construction activities that the delivering materials are used for.

(2) *Space occupancy conditions*

As space is required for performing construction activities, material delivery can be restricted in the case that storing materials in the working spaces create a negative effect on the performance of activities and the quality of constructions. For example, excessive materials stored in the working space spatially interferes the motion of construction workers and decrease productivity of works (Thabet and Beliveau 1997). Moreover, the wrong location of material packages makes construction workers to replace the location of the material packages and it takes work times and manpower. In the case of some types of construction works such as concrete placement and curing, the quality can be damaged when material packages are placed on the floor. On the contrary, construction works such as the fire protection spray can deteriorate the quality of material packages that are placed near working spaces. For those reasons, transportation of materials to the inner space of buildings can be blocked in accordance with the state of working space.

The extent of working space that can be shared with material storing space varies depending on the type of construction activity from activity types that cannot share the space at all to the activity types that is never interfered by storing the material. For representing the extent of the space shar-

ing of activity, the space sharable rate R_o ($0 \leq R_o \leq 1$) is defined. If R_o equals to 0, it means that construction activity cannot allow the working space of the activity to be used by other purposes. If R_o is larger than 0 but less than 1, it means that construction activity can allow sharing the working space as much as the percentage of R_o in the total working space. If R_o equals to 1, it means that construction activity can allow the sharing of the whole space area and they are not influenced by other activities. Before transporting materials in yard storage to the floor space of buildings, material packages confirms whether a construction activity the destination space is allowing the material package to be transported or not based on the percentage of occupancy and the state of the space.

5.3 Model Development

5.3.1 Entire Model Descriptions

The space flow simulation model is comprised of multiple space agents that represent spaces of buildings called space agent (Figure 5-2). Space agent connects to other space agents and the network of them is based on the space hierarchical structure. Therefore, one space agent can be a part of the other space agent, a multiple number of space agent can identically behave to one space agent. Each space agent includes several information such space creation state, materials stored in the spaces, construction activities

occupying or waiting to occupying the space. Based on this information, a space agent autonomously determines how it will respond to requests from external object such as material transportation and construction activities. For example, when materials are prepared to be sent to space agents, those agents calculate the available space at that time or when construction activities try to occupy a space agent for their executions, the agent checks whether there are construction activities that are already occupying the space agent and the results to the construction activities. To analyze spatial conflicts between material flow and activity flow, the simulation model has four primary functions as follows: (1) space hierarchy control; (2) creation space control; (3) activity occupying control; and (4) material delivery control.

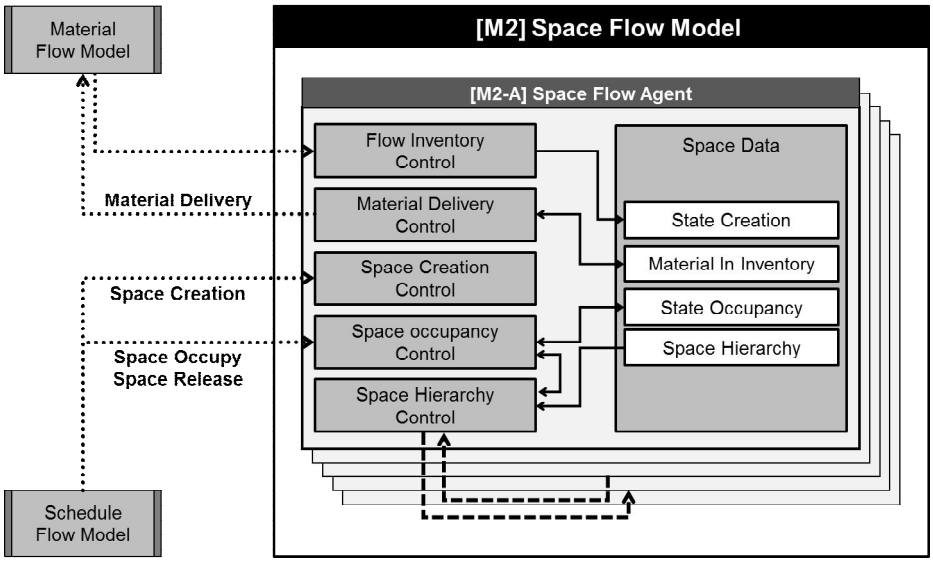


Figure 5-2 Conceptual model of space agents

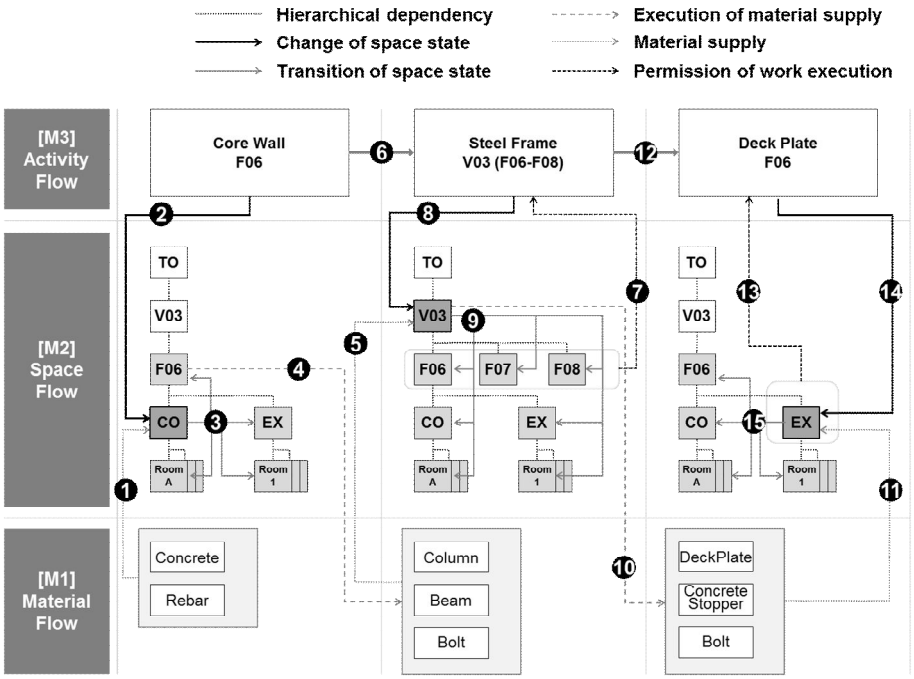
5.3.2 Space Hierarchy Control

The space hierarchy control function aims to synchronize the state of a space agent with those of the other related space agents (i.e., the space creation state and space occupancy state). In the space hierarchical structure, spaces included in different levels have a subordinate relationship. For example, the space that stands for the room on the 6th floor is a part of the space that stands for the 6th floor. Therefore, if the state of one space agent is changed, the change of the state has to be identically reflected to the related space agents in the network of the space hierarchical structure. Moreover, when the availability of a space agent is requested from other functions, it can be determined by considering not only the state of the space agent who is requested but also those of the subordinate space agents because the availability of them can be influenced by other functions. So the purpose of the space hierarchy control function is to prevent an overlapped usage of space which results from the variant concepts in space usages.

5.3.3 Creation Space Control

The creation space control function has the purpose to sequentially change the space creation state of space agents in accordance with the progress of construction. By way of illustration, Figure 5-3 explains the process of change of space creation state. After the core wall work on the 6th floor start and finish, the space creation state of the space agent of the core on the

6th floor (CO) is changed as the core structure is created and then, the state change is transmitted to the other agents on the same floor. Simultaneously, the agent controls the material delivery and the material supply begins, which is only for the activity Steel Frame V03 because the materials of the activity Deck Plate F06 has the unmatched space creation state. In other words, there is no space where the material can be delivered. After all the predecessor activities of the activity Steel Frame V03 such as the Core Wall F06-08 finish and all the space agents change the space state, the activity Steel Frame V03 is executed and the state change process continues sequentially and repetitively.

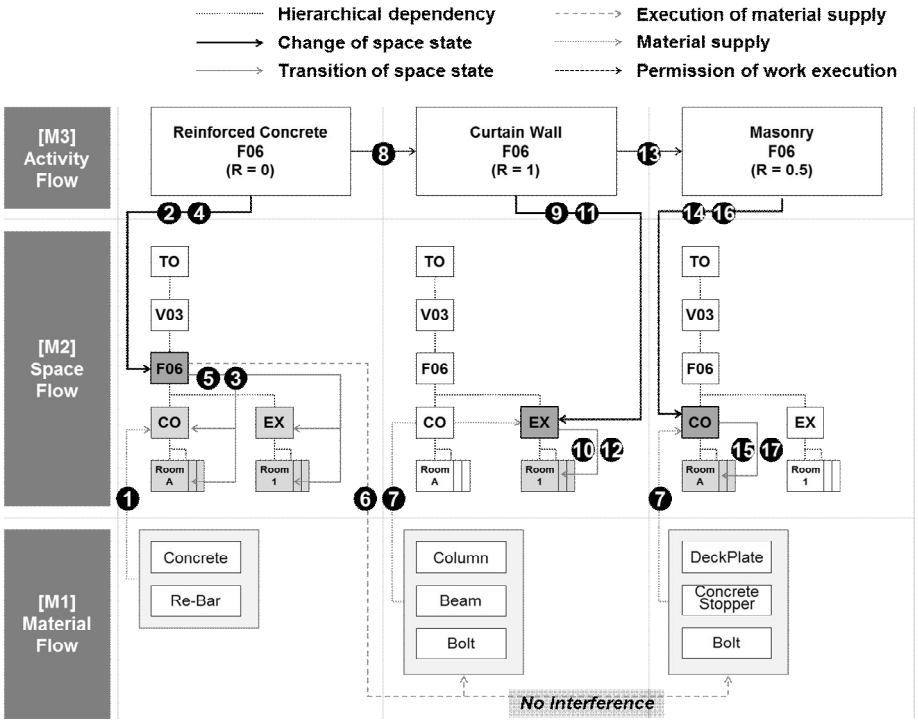


❶ material delivery (concrete, rebar)
❷ change of the space creation state of the space agent (CO) on the 6th floor
❸ transitions of the changed space creation state to space agents on the 6th floor
❹ material delivery control for the next activity (Steel Frame V03)
❺ material delivery (column, beam, bolt)
❻ dependency transitions of the activity (Core Wall F06) to the successor activity
❼ state transition of changed space creation states of relevant spaces (TOV03F06-08)
❽ change of the space creation state of the space agent (V03) on the 3rd vertical zone
❾ transitions of the changed space creation state to space agents on the 6th-8th floor
❿ material delivery control for the next activity (Deck Plate F06)
⓫ material delivery (deck plate, concrete stopper, bolt)
⓬ dependency transitions of the activity (Deck Plate F06) to the successor activity
⓭ state transition of changed space creation states of relevant spaces (TOV03F06EX)
⓮ change of the space creation state of the space agent (EX) on the 6th floor
⓯ transitions of the changed space creation state to space agents on the 6th-8th floor

Figure 5-3 Process of change of space creation state of space agents and interactive behaviors

5.3.4 Activity occupancy control

The creation occupancy control function aims to change the space occupancy state of space agents in accordance with the progress of construction. Figure 5-4 gives an example over the process of the change of the space occupancy state. Before starting the activity Reinforced Concrete (RC) F06, the construction materials associated with the activity are supplied to the space agent F06. However, the construction materials for the next activities such as Curtain Wall F06 and Masonry F06 cannot be transported to the space agent F06 because the space sharable rate of the activity RC F06 is zero, which means that unrelated materials is not possible to be supplied to not only the space agency F06 but also its lower-level agents while this activity are performed. Concurrent with starting the activity RC F06, the space agent F06 is occupied and the space occupancy states of space agent F06 and its lower-level space agents are changed. After the activity finishes, the space agents occupied by the activity are released and the states of them are also changed to not-occupied state. Then, the agents control the material delivery of the next activities, Curtain Wall F06 and the Masonry F06. The reason is, the space sharable rate of the activity Curtain wall F06 is 1 which means that the space occupied by this type of activities can be fully shared for sharing materials for other activities. Also, the space agents occupied by those two activities are not overlapped so that no spatial conflict between them occur during performance.



❶ material delivery (concrete, rebar)
❷ occupancy of the space (F06)
❸ transitions of the changed occupancy state to space (F06)
❹ release of the space (F06)
❺ transitions of the changed occupancy state to space (F06)
❻ material delivery control for the next activities (Curtain wall F06 and Masonry F06)
❼ material delivery both of the next activities (Curtain wall F06 and Masonry F06)
❽ dependency transitions of the activity (Reinforced Concrete F06) to the successor activity
❾ occupancy of the space (EX) on the 6th floor
❿ transitions of the changed occupancy state to space (EX) on the 6th floor
⓫ release of the space (EX) on the 6th floor
⓬ transitions of the changed occupancy state to space (EX) on the 6th floor
⓭ dependency transitions of the activity (Curtain Wall F06) to the successor activity
⓮ occupancy of the space (CO) on the 6th floor
⓯ transitions of the changed occupancy state to space (CO) on the 6th floor
⓰ release of the space (CO) on the 6th floor
⓱ transitions of the changed occupancy state to space (CO) on the 6th floor

Figure 5-4 Process of change of space occupancy state of space agents according to interactive behaviors with activity flow and material flow

5.3.5 Material Delivery Control

The function of the material delivery control is to calculate the inventory level and check the availability of space as material storage in consideration of the characteristics of construction activities that are occupying the space and space area which can be allocated to the materials.

5.4 Simulation Experiments and Results

5.4.1 Experiment Descriptions

Using the space flow simulation model, simulation experiments with the actual high-rise building construction are carried out in order to analyze spatial conflicts between material supply process and construction process. The simulation experiments are comprised of two analyses: (1) to demonstrate that spatial conflicts due a limited indoor space make an negative impact on material supply process, and (2) to examine the trend of creation and occupancy state of indoor spaces during construction for confirming the possibility to increase the efficiency of space usage and reduce spatial conflicts.

5.4.2 Input Data Descriptions

For conducting a simulation experiment, the case data of the actual 50-

story high-rise office building construction case, which is used in the previous study of Chapter 3, is employed. Namely, the material type of the construction material data includes those used for structural works and interior works with the exception of MEP works, while the construction schedule data covers all types of construction works from the 6th floor to the 47th floor. As employed in the case project, the material delivery plan is based on the just-in-time system for all construction materials to arrive at the construction site the day before the relevant construction activity that use the materials is executed.

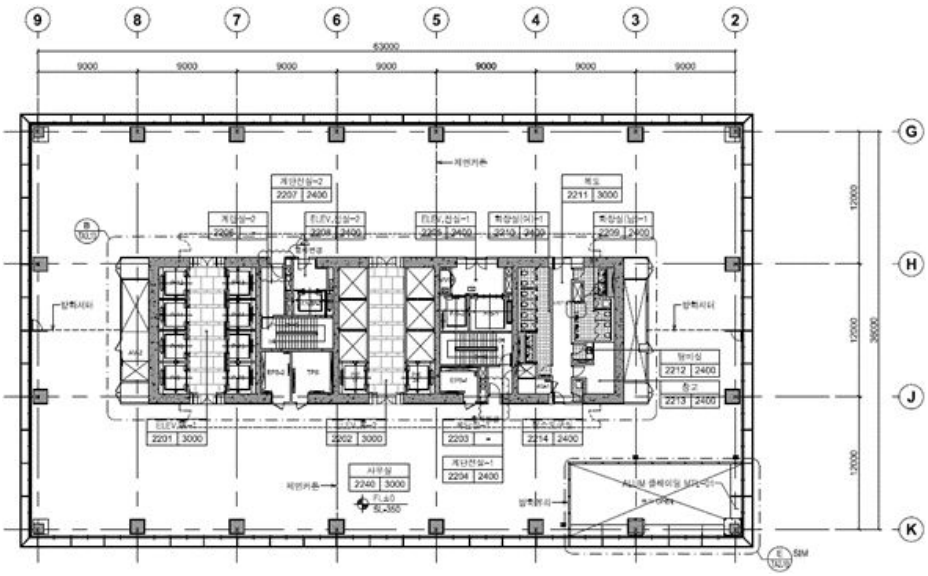


Figure 5-5 Drawing of floor plan of high-rise building of case study

Figure 5-5 shows the floor plans of the simulation case. In consideration of the floor plans, bill of quantity, and construction schedule, the 5-level

space hierarchical structure is developed so as not to mismatch so that different definitions in the material supply plan and construction schedule do not hinder to identify the space conflicts. The sample of the space structure is illustrated in Table 5-1. Furthermore, the space creation state is set up as shown in Table 5-2. The space creates state includes the six different states from core-wall work to partitioning work which can make a critical influence on space structures.

Table 5-1 Sample data of space hierarchical structure of high-rise building in case study

Space ID	**Space Level**	**Space Name**	**Capacity (m2)**	**Upper Space ID**
T1	1	Tower	-	-
T1V03	2	Vertical Zone #3	-	T1
T1V03F06	3	F06	-	T1V03
T1V03F06CO	4	Work Zone Core	-	T1V03F06
T1V03F06COELH1	5	ELEV HALL #1	36	T1V03F06CO
T1V03F06COELHM	5	ELEV HALL	36	T1V03F06CO
T1V03F06COEPS1	5	EPS-1	9	T1V03F06CO
T1V03F06COEPS2	5	EPS-2	13.5	T1V03F06CO
T1V03F06COEVF1	5	ELEV Front #1	13.5	T1V03F06CO
T1V03F06COEVF2	5	ELEV Front #2	9	T1V03F06CO
T1V03F06COTLWM	5	Toilet (Woman)	36	T1V03F06CO
T1V03F06COTPS1	5	TPS-1	16	T1V03F06CO
T1V03F06COTLMM	5	Toilet (Man)	36	T1V03F06CO
T1V03F06EX	4	EX	-	T1V03F06
T1V03F06EXOFFA	5	Office	1620	T1V03F06EX

Table 5-2 Level of space creation states

Space Creation Integer Code	Space Creation State Name
Level 1	Core-wall
Level 2	Structural frame
Level 3	Deck-plate
Level 4	RC
Level 5	Curtain-wall
Level 6	Partitioning

5.4.3 Simulation Results

Analysis 1: Occurrence of conflicts between material supply process and construction process

(a) Result 1-1: Storage Times of Materials in Yard Storage until Transportation Permission

The storage times of materials in the yard storages are measured in order to examine the existence of the influence of the construction process on material supply process. Materials that are stocked in the yard storages have to satisfy two conditions to be delivered to work spaces inside of the building: (1) available hoisting equipment, and (2) available storage space in the

work space. Therefore, to remove the delay effect of the shortage of hoisting equipment, the storage time is measured as having the time range from when stored to when allowed to be transported to space agents without any conflicts.

Figure 5-6 shows the discrete probability distribution of the average storage time of materials in the yard storage, and the variation according to capacity of yard storages is shown together in the chart. In all the cases, the storage times of more than around 25 percentage of the materials are larger than or equal to two days and the results show no distinction according to the capacity of the yard storage. It means that those materials cannot be permitted to be transferred to their work spaces in one day and are remained as stocks in the storage due to the conflicts to the construction process which occupies the spaces of buildings. As the material deliveries are scheduled to begin the day before the related activities are performed, the storage time longer than one day has the possibility to cause other schedule problems owing to the delay of the material delivery.

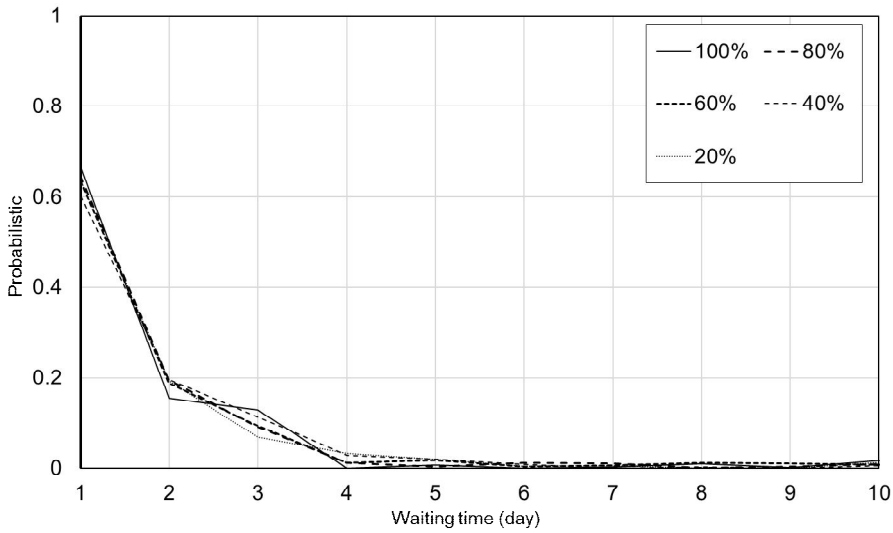


Figure 5-6 Storage times of material packages in yard storages from stored to permitted transportation into work space

Analysis 2: Variation of Space Occupancy during Construction

(a) Result 2-1: Variation of Space Creation States of Space Agents during Construction

The change of the space creation states of the space agents is investigated through the simulation experiments. Figure 5-7 illustrates the change of the number of space agents that have various types of space creation state from the level-1 to the level 6. Because of the space creation states that are changed along the progress of construction schedule, the patterns that the number of each type of space creation states increase linearly. For examples, the numbers of the level-1 and level-6 space creation states that generated by

core-wall works and curtain-wall works, respectively, increase consistently.

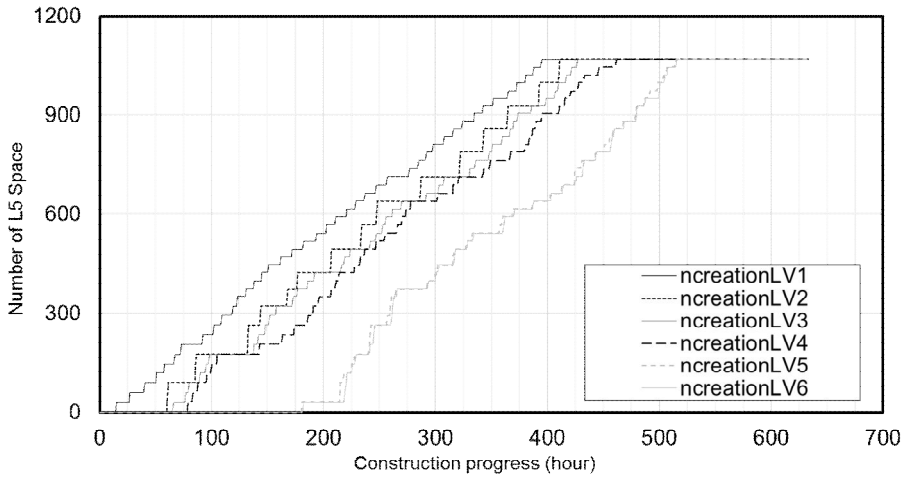


Figure 5-7 Variation of number of space creation states of space agents during construction

(b) Result 2-2: Variation of Available Space for Storing Material Packages

For the next step, the number of available spaces for material storage is examined. As the construction activities of the structural works (e.g., the core-wall work, steel frame work) are related to the change of the space creation states, the construction materials for those activities cannot be delivered before the corresponding activities are executed, therefore, it is difficult to utilize empty space on the same floor which is not occupied with other activities. While, a number of construction activities of interior works (e.g., tiling, furniture installation), which are conducted after the curtain wall works, are not concerned with the change of the space creation, it is possible

to be transported before the corresponding activities begin if the condition of the occupancy states of predecessor activities is satisfied. Hence, the number of space agents that have the level-6 space creation states and that are occupied by construction activities are compared to investigate how many space agents.

Figure 5-8 shows the change of the number of the level-6 space creation spaces and not-occupied spaces. The number of space agents of which the space creation state becomes to equal the level-6 increase linearly in accordance with the progress of curtain-wall works. However, the number of space agents occupied by construction activities for their performance takes a smaller percentage in the level-6 space agents as the progress goes on. Despite the fact that the spatial interference in transporting material deliveries incurs due to the availability of space, actually, it comes out that a large number of spaces remain as empty spaces which are not used both for construction performance and material storage.

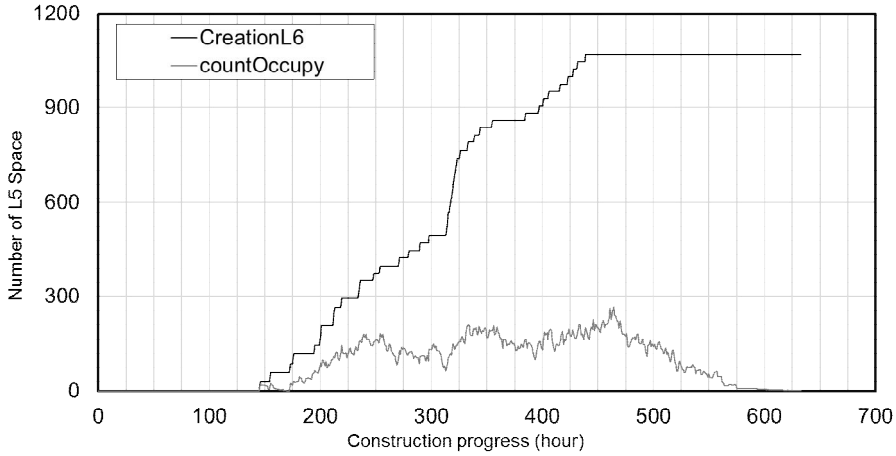


Figure 5-8 Variation of the space creation space for the level-6 and available spaces to material storage in the buildings

5.5 Discussions

In construction management, material supply process is considered as one of the key factors affecting construction process in the form of material shortage or delivery rate. However, the construction process is regarded as having no effect on material supply process. In the perspective of SCM, construction and material supply processes is a single process that is comprised of a series of continuous activities. Therefore, construction activities in the successor step do not generate any effect on activities of material supply in the predecessor step. Even in a pulling system, delays of a construction process do not cause an additional impact on a material supply process because a process flow is synchronized.

In supply chains of high-rise building constructions, however, conflicts between those two processes can occur. As aforementioned in the previous chapters, as there are many cases of lack of yard storage spaces, dissimilar types of material supply processes have to share the same yard storage. Even though the inventory level of individual processes can be minimized based on the Just-In-Time (just-in-time) method, these optimizations cannot ensure that the total inventory level will not exceed the storage capacity. In order to decrease the negative effect of these interferences between two processes, therefore, it is necessary to reduce a storage time in the yard storage by transporting materials into workspace inside of buildings as soon as possible.

However, in many cases, internal spaces that construction activities are performed are not sufficient in order to cover all of delivered materials. The available capacity of internal spaces for materials is dynamically changed according to the progress of construction activities, because these spaces are transformed by construction activities and the spaces that have to be used for performing construction activities are changed dynamically. For example, the floor area that material packages put on is definitely changed after slab construction works. During spray-painting works, little space can be used for storing materials owing to working spaces as well as quality degradation problems of delivered materials. Hence, in the case that inner spaces are not enough to cover the material delivered from the yard storage, there is the possibility that material delivery processes are directly interrupted.

For these reason, this research was conducted with the objective to demonstrate that such space conflicts between construction and material supply processes can occur and their impacts have a significantly negative effect on construction production systems. Through the simulations with the actual case, it is confirmed that transportation tasks of materials from the yard storages to workspace can be delayed due to the lack of the capacity of internal spaces. The 30 percentages of material packages are delayed longer than the daily working hour (8 hours), which can directly cause a negative effect on the relevant construction activities in the just-in-time methods, where all construction materials are set up to be delivered the day before the executions of those construction activities. In addition, the results suggests that the overall construction durations in the case of considering these spatial conflicts are significantly worth than those in the case not to consider them.

In this research, the process that the spatial conflicts are spread along the networks of supply chains was not analyzed in a quantitative way in order to more clarify the relationship of the spatial conflicts and performance of construction systems. However, in the light of the findings in the previous chapters, these results can be interpreted as follows. Spatial conflicts interrupt construction materials to be transported from the yard storages to the internal spaces, and it increases the total inventory level in the yard storages and the possibility that the interferences between material supply processes occur. These interferences have a negative effect on the construction activities by delaying the delivery of construction materials. As the delayed con-

struction activities are able to incur the spatial conflicts again, the impact of the spatial conflicts repetitively continue affecting the construction and material supply processes. On some occasion, the variability caused by the space conflicts may be absorbed into buffers included in the construction and material supply processes, On the contrary, they may affect activities and materials involved in critical path, which causes a negative effect on a whole construction project. For these reasons, when we controlling construction supply chain, it is difficult for us to identify the cause and effect of the variability, which results from the spatial conflicts and affects the whole system.

Furthermore, this research analyzed the variation of the occupancy rate by construction activities while the spatial conflicts are incurred. The total area of the internal spaces increases according to the progress of construction process, however, the area occupied for performing construction activities did not increase consistently. Despite the fact that the spatial conflicts occur during construction, the reason why the occupancy rate did not shows a high level can be considered that the spaces necessary for performing activities and storing materials is not uniformly distributed to all internal spaces, but concentrated in parts of internal spaces. Therefore, in order to increase the utility rate of internal spaces and prevent the spatial conflicts, the method to efficiently use internal spaces are required. As the availability of internal space is dynamically change, inadequate plans can interrupt other construction activities and generate handling costs due to frequent moving of materials. Particularly in the case that materials are stored on other floors, material

supply processes can be adversely affected owing to the increase of the load on insufficient hoisting equipment. Thus, further research will include the optimization method of the usage of the internal space in consideration of the characteristics and relationships of construction activities, resource, and materials.

5.6 Summary

The purpose of this research is to investigate whether the spatial conflicts occur due to lack of internal space of buildings and to what extent these conflicts create an adverse effect on construction supply chains. To achieve those goals, I developed an agent-based simulation model that can represent behaviors of space agents as to the state of space creation changed by construction activities and the state of space occupancy affected by both construction and material supply activities. This model performs a role in controlling the processes of construction and material supply, according to the state of space they require, so that it is possible for the developed model to answer the key questions of this research. Based on this model, simulation experiments were also conducted using real data of high-rise building constructions in this research.

By analyzing the results of those simulation experiments, it was verified that a material supply process can be interfered by the change of a construc-

tion process and this can have a negative effect on a construction process. Namely, complex behaviors of the interrelated components of construction and material supply can create interferences, which cannot be deduced from the characteristics of individual components.

Chapter 6. Impact of Material Supply Strategy on Complex Behaviors in Construction Supply Chains

6.1 Introduction

In construction management, contractors' strategies on the inventory level have a significant impact on the performance of construction projects. Generally, if the inventories in processes increase, the cost for handling and storing those inventories increases. Whereas, holding a too small amount of inventories has the possibility to increase a loss involved in delays of construction activities because these inventories cannot mitigate the negative impacts of material shortage and delivery delays resulting from the unexpected risk events in material supply processes. Therefore, it is important to determine an appropriate inventory level for successfully managing construction projects.

In high-rise building constructions, due to lack of the limited resource capacity for material supply (e.g., yard storage space, hoisting equipment), an uncommon relationship between the inventory level and the performance of projects may be established due to the interferences between material supply processes that share insufficient resources. For e example, holding excessive inventories in construction sites increase those interferences and

their negative impacts, while, to hold too small amount of inventories make it difficult to compensate for delivery delays of materials caused by the interferences. Hence, the relationship between the inventory level and overall construction durations become more complex to understand.

The objective of this research is to investigate the relationship between the on-site inventory level and project's performance as aimed in the Hypothesis 4. The first step to achieve this goal is to develop a simulation model, which represents the complex behaviors of the interactive components of construction supply chains and control on-site inventory level of construction materials under the condition that different types of material supply processes interfere with each other due to lack of supply chain resources. Thus, a material supply method for controlling inventory level is developed, then combined with the simulation models developed in the previous chapters. Simulation experiments with real data of high-rise building construction projects are performed in order to examine the relationship between on-site inventory level and the performance.

6.2 Strategies on Material Supply and Inventory Management

In order to examine the relationship between the inventory level and project's performance, it is necessary to determine a inventory management

method regarding in which conditions and how much construction materials are to be supplied to construction sites. Traditionally, there are two different concepts in material supply and inventory management method, Just-In-Case (JIC) and Just-In-Time (just-in-time) (Polat and Arditi 2005).

In JIC methods, which exemplified by the Economic Order Quantity (EOQ) model, material order is repetitively conducted when the inventory level of materials decreases until the safety inventory level (Min and Pheng 2005). In this case, the order quantity of materials is calculated based on EOQ that minimizes the total cost for holding and ordering materials. As this method holds a larger amount of inventory than the safety inventory level in order to prevent material shortages, if the demand rate can be estimated properly, the material shortages never happen. Therefore, this method is based on the following assumptions: (1) constant demand rate, (2) product by product management, and (3) no material shortage and overload (Fazel 1997; Fazel et al. 1998; Min and Pheng 2005).

Even though this traditional just-in-case method provides an intuitive explanation for the relationship of the cost and inventory level, there are several difficulties to apply this to high-rise building construction projects under resource-limited conditions. First, the concurrent construction process do not ensure a constant demand rate because it varies depending on the schedule of construction works. Moreover, this method cannot calculate the inventory level in the case that multiple types of material supply process share the

same storage and warehouse due to the insufficient capacity of them. For those reasons, this method is difficult to apply to high-rise building constructions in the context of the supply chains of high-rise building construction projects.

On the other hand, in the just-in-time method, supply of materials is synchronized with demand (Akinyote 1995). Just-in-time method regards inventory as wasteful, so that this method aims to keep the minimum amount of materials, WIPs, and product in production systems (Choo and Tommelein 1999). In order to achieve this goal, all materials are delivered right before tasks are executed and all tasks are executed after all produced inventory are delivered to the next tasks. Therefore, just-in-time is a kind of demand-synchronized methods, namely, a pulling system.

In spite of these advantages of the just-in-time method, some limitations have been pointed out in supply chain literature. Firstly, this method is susceptible to risk events in terms of material supply. As this method does not set up a safety inventory during constructions, the failures in material delivery on time directly lead to construction delays (Shmanske 2003). Secondly, yard storage space for storing delivered materials does not require additional cost during construction and no additional cost is generated for keeping safety inventory that can perform a role as capacity buffer. Therefore, within the limits of inventory capacity levels, to keep safety inventory is effective to avoid a failure of material supply (Polat 2007). Finally, as the quantity of

material supply is determined only based on demand and the capacity of inventory leave out of consideration in this method. Thus, just-in-time cannot ensure to prevent that the inventory level exceed the capacity of the storages in the case that the capacity is extremely limited. In high-rise building constructions as mentioned in the chapter 4, the various material supply processes have to share limited yard storage spaces, so that the total inventory level can frequently exceed the capacity of the storage.

6.2.1 Demand-Synchronized Material Supply and Inventory Management Method

In consideration of the advantages and disadvantages both of just-in-case and just-in-time methods, in this research, a demand-synchronized material supply method is employed for controlling the material supply and inventory level with the strategy. This demand-synchronized material supply method also calculate the quantity of material orders based on the demand from construction activities as the just-in-time method, however, this method does not aim to deliver construction materials right before construction execution and to minimize the inventory level. On contrary, this method is allowed to hold enough inventory in yard storages by supplying materials earlier than one days before construction activities are executed. In this method, construction managers control the number of days when materials have to be supplied before activities' execution (Figure 6-1).

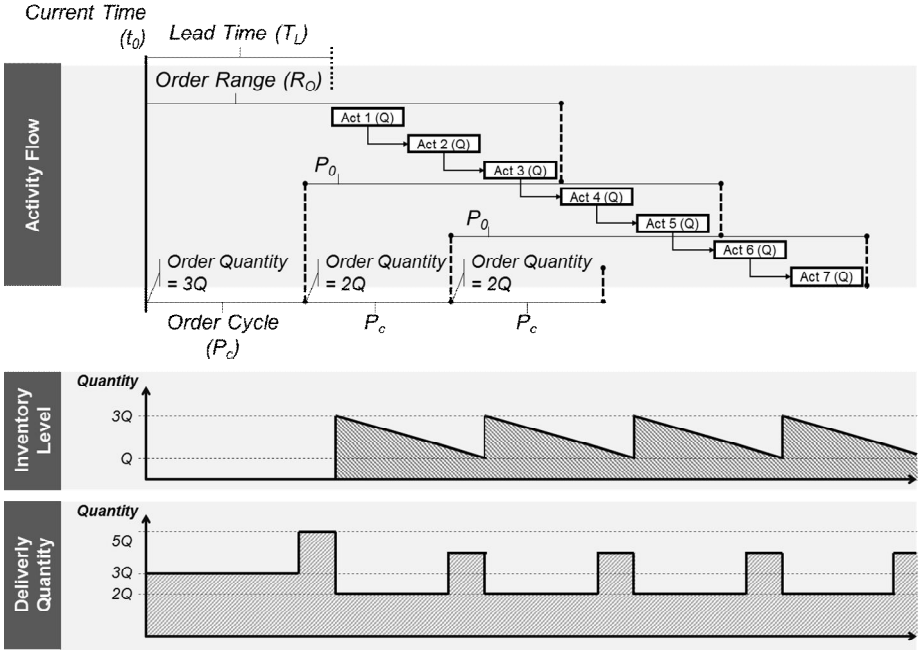


Figure 6-1 Calculation method of material order quantity and variation of inventory level and delivery quantity

6.3 Model Development

6.3.1 Entire Model Descriptions

An information flow simulation model is developed as a single agent-based simulation model and has an important role in estimating the progress of construction activities and controlling the quantity of material supply and inventory level based on the demand-synchronized inventory management

method. To develop a feedback system integrating a construction process and a material supply process, the material flow model in Chapter 3 and the activity flow model in Chapter 5 included in the development of the information flow model. As shown Figure 6-2, the simulation model has the following four primary functions: (1) monitoring, (2) forecasting, (3) calculating, and (4) ordering.

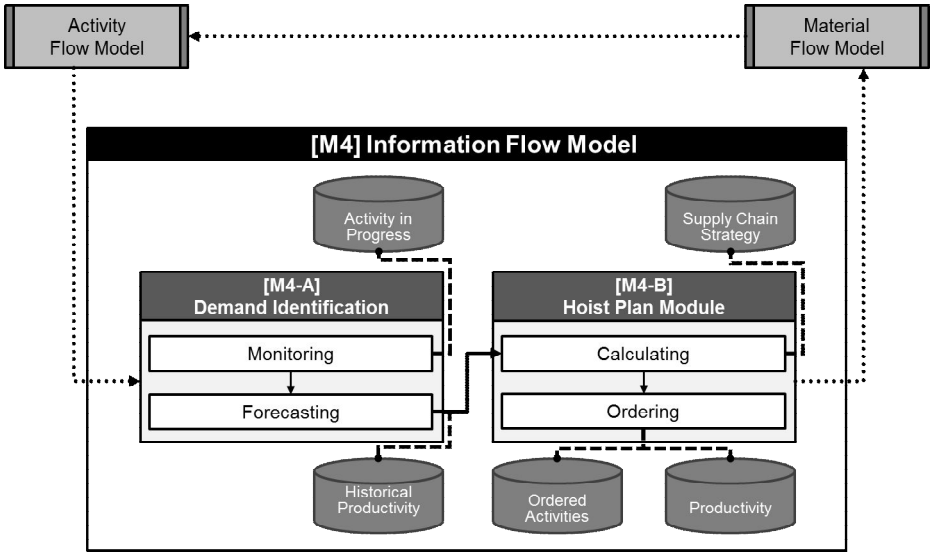


Figure 6-2 Conceptual model of single agent in information flow

6.3.2 Monitoring and Forecasting Construction Activities

Monitoring and forecasting functions aims to identify construction activities that are supposed to begin in the near future in order to confirm de-

mands for material delivery. The monitoring function collects information about ongoing activities, and the estimating function calculates start and finish times of not only on-going activities, but also predecessor activities in consideration of schedule dependencies on them.

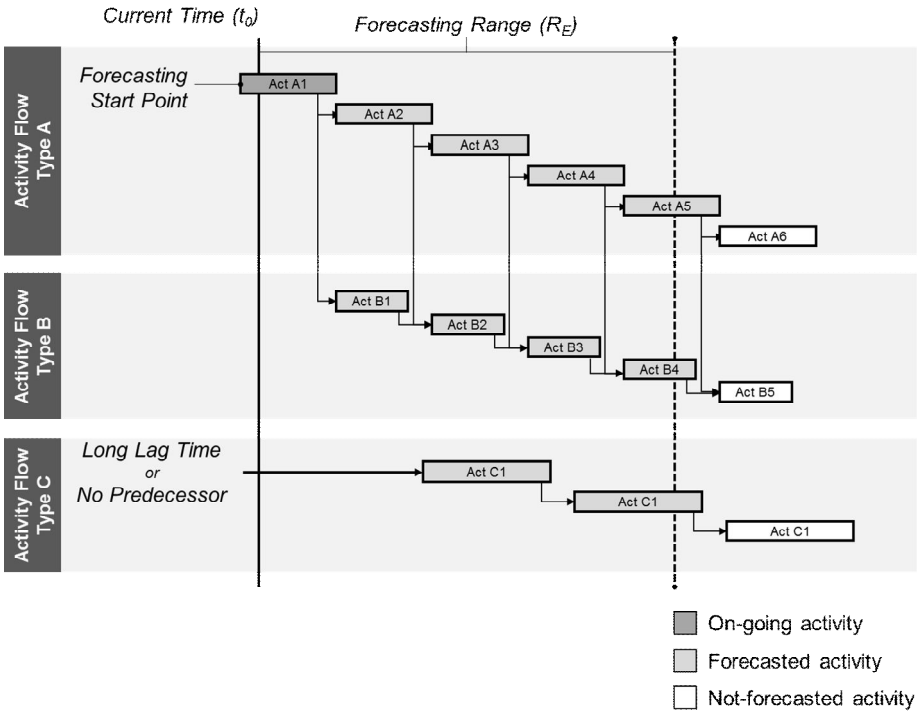


Figure 6-3 Forecast of start and finish times of construction activities

(1) *Monitoring Function*: owing to schedule risks, there is a possibility that a construction process is fluctuated and it can completely change demands at a specific time. The monitoring function collects information on which construction activities are in progress of construction, how much time these ac-

tivities have been already performed, and how many time these activities could not be performed by internal and external risk events (e.g., material shortage, increment weather condition). In additions, among construction activities included in schedule, there are activities that have no predecessor activity and are executed by own independent schedule. The monitoring functions separately monitor the remaining time before these activities begin. This function repetitively operates after daily schedules finish with a daily cycle and transfers the collected information to the predicting function.

(2) *Forecasting Function*: The forecasting function identifies demand of material supply from construction activities. The forecast starts with the activities monitored by the monitoring function and repetitively forecasts the start and finish times of construction activities according to the schedule dependencies on them. As illustrated in Figure 6-3, the forecasting process is conducted activity by activity, and after schedule of one activity is calculated, the schedule of successor activities is forecasted sequentially.

As the first step of the forecast, the forecasting time range D_{pred} is initially set in order to decide the activities whose materials are supplied. If among material types, the largest number of days for the demand-synchronization method is D day, the forecasting time range (R_{fore}) becomes $D+1$ because the progress of construction of the D+1 days ago should be utilized for forecasting construction schedule.

The calculation of construction schedule begins with forecasting the finish times of ongoing activities. As the start times of those activities are already known, the duration of each activity should be estimated for the finish time. Durations can be considered as the sum of working time and non-working times caused by external risk events. As activity durations can be stochastically changed, the average duration of predecessor activities is utilized to estimate the durations and finish times of the on-going activities. The finish time (T_F^{na}) of the n-th activity of the activity type a is defined as the following equation:

$$T_F^{\mathrm{n}_a} = T_S^{\mathrm{n}_a} + \sum_{i=a-N_p}^{a-1} D_{act}^{(\mathrm{i})} \cdot N^{-1} + T_D^{\mathrm{n}_a} \tag{6-1}$$

where T_S^{na} is the start time of the n-th activity of the activity type a; N_p is the number of predecessor activities which are used for calculating the average of duration of the activity type a; D_{act}^{i} is the duration of the i-th activity; T_D^{na} is the delay time that already happens during performing the n-th activity. After the duration and finish time of activities are done, the successor activities of them are sequentially estimated in consideration of the type of dependency (e.g., start-to-start (SS), finish-to-start (FS)) and the lag-time of dependency until the start time of successor activity is smaller than the forecasting time range R_{fore}. According to the process shown in Figure 6-4, the schedule of the activities are estimated in a sequential way.

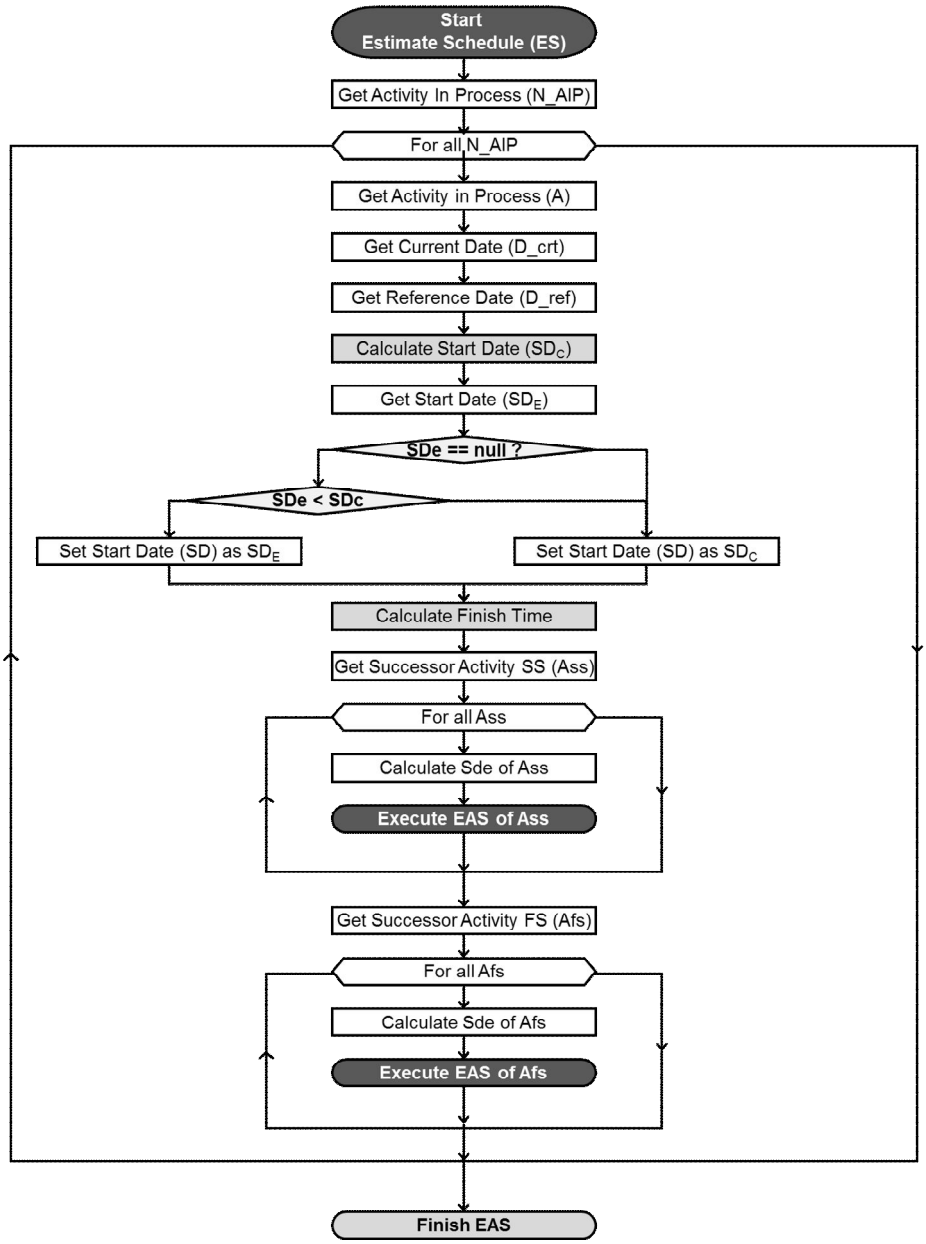


Figure 6-4 Algorithm of sequential forecast of construction activities

6.3.3 Order Quantity Calculation

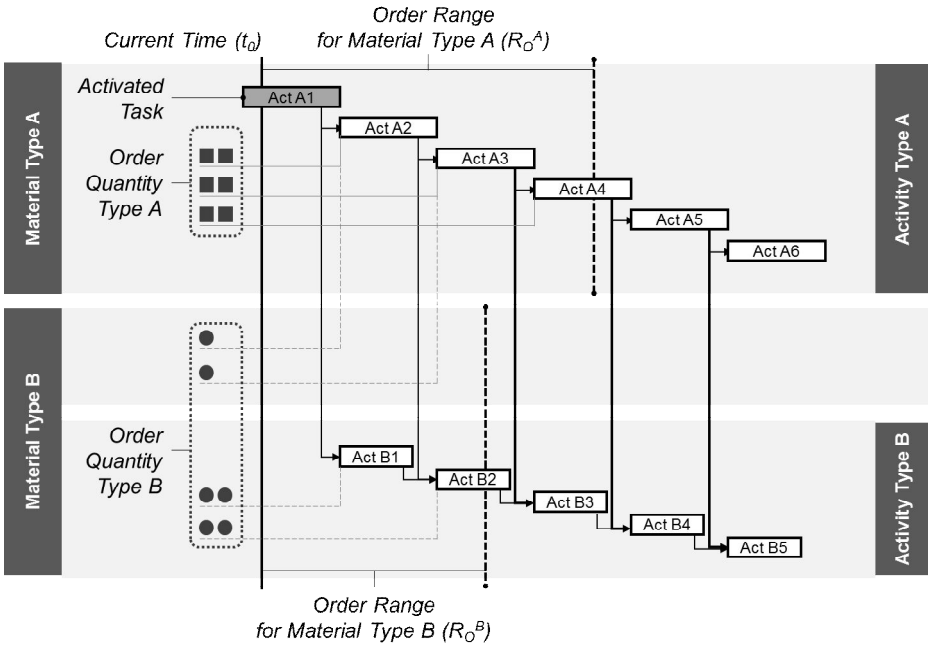


Figure 6-5 Calculation of material order quantity with different order range by work type in demand-synchronization method

Based on the results of demand forecast of the construction process, the order quantity is calculated by material type. Among the construction activities of which schedule is estimated, only the activities of which delivery orders are not made are used for calculating the quantity of delivery orders. As illustrated in Figure 6-5, the order range can vary according to type of construction material. In the case when one activity utilizes two more types of materials, the delivery orders are made separately even though they are included in the same activity. After the calculation of the quantity of delivery

orders are done, the results are transmitted to the warehouse of suppliers.

6.4 Simulation Experiments and Results

6.4.1 Experiment Descriptions

Simulation Experiments are conducted to examine the relationship between the inventory level and overall construction duration. According to the number of days that materials have to be delivered before construction activities begin, the inventory level are controlled based on the demand-synchronized material order methods. The number of simulation iterations for one type of initial condition setting are 2500 times. The average value of construction duration of each setting are employed as the simulation result. The case of the high-rise building construction project used in the Chapter 3~5 are applied to this simulation experiments in the same way.

6.4.2 Simulation Results

Analysis 1: Variation of Construction Duration according to Material Supply Strategies

(a) Result 1-1: Relationship of Inventory Level and Construction Duration

Figure 6-6 shows the variation of construction durations according to the number of days before construction activity execution. In the case that the simulations are set up for construction materials to be delivered one day before the construction activities begin, the simulation result exhibits the worst performance in construction durations. However rather, in the case that materials are delivered earlier than one day before the construction activities start, the construction duration are shorten. When construction materials are delivered 4-14 days before the task executions, the simulation results show similar duration with small deviations. However, with the more increase of the number of days, construction duration slowly increased again.

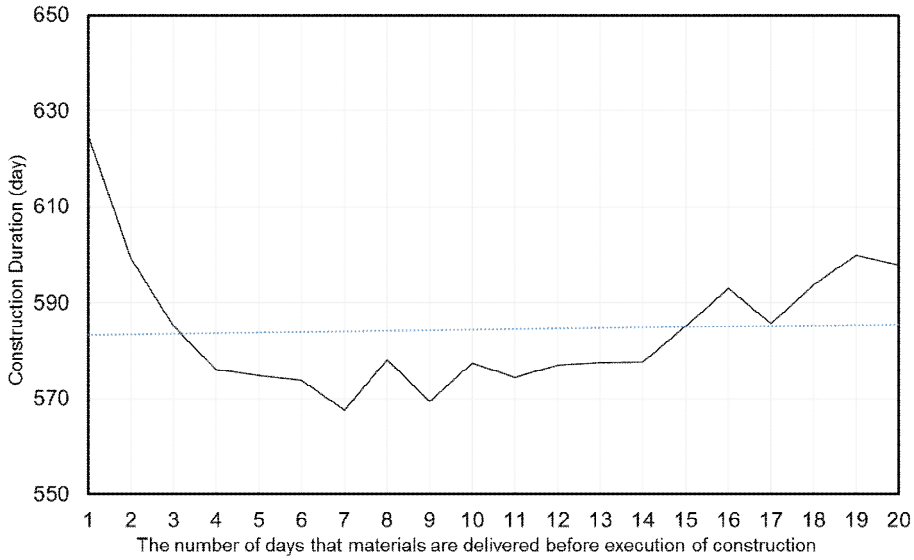


Figure 6-6 Variation of construction duration according to number of days of material delivery before execution of construction

6.5 Discussions

Contractors' strategies on on-site inventory level have significant effects on the performance of construction production systems. For example, holding a large amount of inventories during construction becomes the cause of additional expenses because a large amount of resources have to also be secured for keeping the inventories, while holding a small amount of inventory makes a construction production system vulnerable to the variability of material supply processes, which also causes the additional cost for construction delays. Accordingly, in the case that material supply processes have the variability, too small inventory may be as detrimental as too excessive inventory.

However, even in the case that materials are uniformly supplied without the variability, the performance of construction supply chain can be aggravated due to a small amount of inventory. As mentioned in the previous chapters, the interferences and spatial conflicts within and between construction and material supply processes may cause an adverse effect causing delays in material supply processes. Therefore, if too small amounts of inventories are held in construction sites, the delays of material supply processes become a direct cause of construction delays. On the other hand, those interferences are incurred when the total inventory exceeds the resource capacity shared by multiple material supply processes. Therefore, too large amounts of inventories in construction sites also become a cause of increasing those interferences and their negative effects. Accordingly, in both cases to in-

crease and decrease the on-site inventory level, an overall duration of construction projects can produce deteriorated consequences.

For those reasons, this research was conducted to clarify the relationship between the inventory level and overall duration of a construction process. The results of the simulation experiments suggest that the simulations that are designed for construction materials to be delivered on the day before the executions of the relevant construction activities show better performances than those to be delivered on the earlier days before their executions. As the delivery date is moved earlier and earlier (namely, as the inventory level increases), the overall construction duration decrease. After passing the minimum point, however, it begins to increase again.

The relationship between the inventory level and overall construction duration can be explained as follows. In the case that the amount of the on-site inventory are minimized, delays of material supply process due to the interferences directly causes the delays of construction activities. However, with the increase of the inventory level, an overall construction duration decrease because the increment of the inventory level plays a role as buffers to reduce the delays. As the capacity of the yard storages is fixed, the amount of the safety inventory cannot be increased unlimitedly. After the inventory level reaches the maximum value, therefore, the positive effect of the safety inventory does not increase. Meanwhile, with the increase of the inventory level, the interferences in processes continually increase and it lengthen lead

times and cause delays of parts of material supply processes, which can lead to the increase of the overall construction duration. Hence, the inventory level can be considered to have a non-linear relationship with and the construction duration.

To sum up, in the case that the interdependent relationships that can generate the variability exist among the components of construction production systems, the just-in-time method, which optimize the individual flow process cannot ensure that the performance of the whole system is maximized. Those interference occurring in the processes is irregular and temporary and their impact on the whole system is indiscernible. Therefore, this relationship cannot be identified based on analyzing the properties of individual processes. For more maximizing the performance of construction production systems, it is important not only to minimizing each component, but also to consider the relationship between system's components.

6.6 Summary

This research was carried out in order to examine the relationship of contractors' inventory strategy and performance of construction supply chains of high-rise building constructions. The inventory level can be highly fluctuated because various types of material supply processes have to share insufficient resources and this situation becomes a cause of interference and

conflicts in construction and material supply processes, which makes the relationship between the inventory strategy and construction performance more complex.

To examine this relationship, firstly, a demand-synchronized method was designed, which is able to control the number of days before construction activities are executed. Then, the simulation models developed in the previous chapters were extended incorporating a demand-synchronized material order method, so that the model is able to predict the amount of the material delivery order for the near future, by monitoring information on the progress of construction schedule. Using this simulation models, finally, simulation experiments were conducted for confirm the Hypothesis 4 regarding the relationship of the inventory level and performance of the construction process.

Through the experiments, it was found that both cases of holding too small and large on-site inventory have a negative effect on an overall duration under the conditions that inherent interferences among processes sharing resources exist. Namely, the inventory level have a non-linear relationship with an overall construction duration even under the condition that material supply processes are not interfered by any external factors. The reason for this relationship can be considered that the safety inventory over a certain amount is necessary to eliminate the negative effect of the inherent interferences, while excessive inventories increase the negative effects, which can

lead to delays of construction process. Such negative effects from the inherent interferences is difficult to be controlled by the previous methods, which aims to optimize the inventory level of individual processes.

Chapter 7. Variable Relationship of Supply Chain Strategy and Project Performance according to Risk Environment

7.1 Introduction

Due to the nature of project-based production systems, construction projects are conducted in various locations in the world, which have different types and extents of external risk factors affecting the construction projects. For analyzing an environmental effect on the construction project, researchers have carried out analytical studies to identify risk factors by type of facility and quantify their impact on project performance. Many of those researches are based on the assumption that: (1) the impacts of various risk factors on construction projects are independent of each other and (2) construction projects are constant and static systems, so that the relationship between contractors' strategy and project performances is also constant regardless of the risk environment.

However, those previous researches based on a reductionist approach have a limitation to explain their relationship. A construction project is a dynamic and complex system, which is comprised of diverse components and sub-systems that are interactive and interdependent with one another. The risk factors have different effects according to the characteristics and current

state of the components and sub-system, and, those impacts are diffused through the locally-connected network of components, which make the impact of risk factors more partial. As a result, it has the possibility to change the behaviors and relationships between components, consequently, even the behaviors of the whole system. Thus, when construction managers develop strategies on their construction supply chains, the impact of risk factors can change the expected performances of construction projects through their strategies, by changing the behaviors of the project components.

For these reasons, this research aims to demonstrate that the relationship between external risks and project performance is not constant and linear, but changed depending on risk factors. To achieve this goal, firstly, I developed a simulation model that represents complex behaviors of construction projects. A simulation model is developed by integrating four simulation models, activity flow model (Chapter 3), material flow model (Chapter 4), space flow model (Chapter 5), and information flow model (Chapter 6) whose complex behaviors are already examined in the previous chapters. For reflecting the impact of external risks, synthetic risk generators causing delays in construction and material supply processes are added to a simulation model. Secondly, a cost model that consists of cost elements regarding supply chain and construction is also developed to diversify performance measures of construction projects, so that a simulation model will provide more various information on the variation of project performance due to external risks. Finally, simulation experiments are conducted using a simula-

tion model in order to examine the variation of the performance of construction system and its components according to the type and extent of external risks on construction and material supply processes. This research also provides a discussion on the results from simulation experiments and findings on construction projects.

7.2 Model Development

7.2.1 Model Development

In order to examine the impact of external risk factors that cause delays in construction and material supply processes, a simulation model that represents the complex behaviors of construction supply chains of high-rise building construction is developed by integrating the four simulation models developed in the previous chapters: activity flow simulation model, material flow simulation model, space flow simulation model, and information flow simulation models. In addition to this, two types of the external risk generation model that randomly generates delays in an activity flow and material flow, respectively, are developed and combined into the entire model. Figure 7-1 illustrates the components and structures of the developed simulation models and the descriptions of each component are as follows.

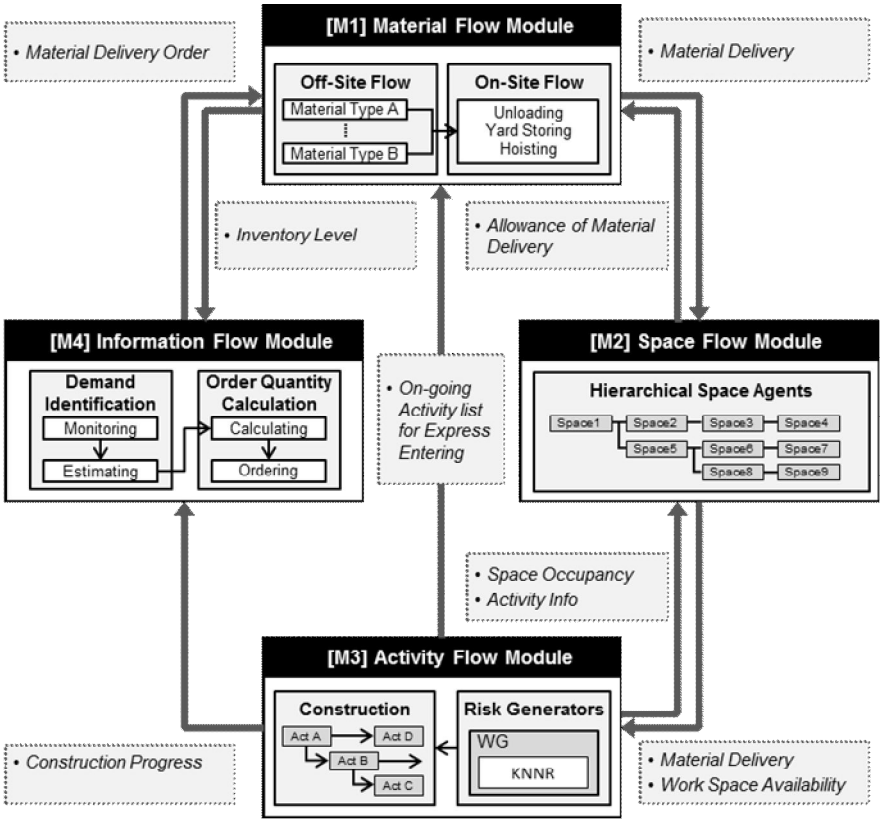


Figure 7-1 Conceptual model of structure of integrated simulation model and relationship between models

(1) *Material Flow Model*: the material flow model perform a key role in representing material supply process from suppliers to work spaces in construction sites according to the material delivery orders. In the process of material supply, the model communicates with other models in the three ways. Firstly, information on the material delivery order to determine the time and quantity of material supply are transmitted from the information flow model. Secondly, the activity flow model updates the information on the on-going construction activities. In order to reasonably supply construction materials, even

when the yard storages are full, but do not include the materials of the on-going activities, material packages of on-going activities are transported not via the yard storages. Finally, material packages in the yard storages can be transported into workspaces according to the availability of spaces related to the destinations of materials which is determined by the space flow model.

(2) *Activity Flow Model*: activity agents in the activity flow model are operated according to the start and finish events. The start event of each activity agent is triggered when the following prerequisites are satisfied: (1) all of the predecessor activities complete their tasks; (2) all the materials for the construction activity are delivered; (3) all the workspaces of the construction activity are available; and (4) no non-working condition occur. The information required for triggering the activity execution is obtained from other types of simulation models.

(3) *Space Flow Model*: space agents interact with the agents of the material flow model and activity flow model, who want to occupy the space agents in order to accomplish their given tasks. The material flow simulation model requires the information on the availability of space for transporting construction materials into workspace, and the activity flow model requires the information on the availability for performing the construction activity. When they request information to the space flow simulation model, each space agent determines the availability of the space in consideration of states of space creation and occupancy of the agent itself as well as those of other

space agents at lower levels in the space hierarchical structure.

(4) *Information Flow Model*: As the progress of construction and material supply is constantly changed during construction, the information flow model repetitively collects the information on the progress of the construction process from the activity flow simulation, predicts the construction activities that will begin in the near future, and calculates the quantity of construction materials to be ordered according to strategy on the on-site inventory level. After determining material delivery orders, the information on these are transmitted the off-site material flow models.

(5) *External Risk Generation Model*: there are two different types of external risk generation models, one is for a construction process and the other is for a material supply process. These models have the probability of the occurrence of delay events and determine stochastically whether tasks in these processes will be delayed or not. The delay events in the activity flow simulation model are determined by task, and delays events in the material flow simulation model are determined by transportation vehicle. If the delay events occur, the selected tasks are halted for one day.

7.2.2 Cost Model for Performance Measure of Construction Supply Chain Management

A performance measure is developed for measuring the cost perfor-

mance of construction supply chain management. As shown in Figure 7-2, the project cost is comprised of the construction cost and supply chain cost. The construction cost is the cost for materials, labor, and direct expense, and in this study, it is assumed that the construction cost is not changed during construction. The supply chain cost can change depending on strategy on supply chains and given conditions. The elements of the supply chain cost and explanations on them are as follows:

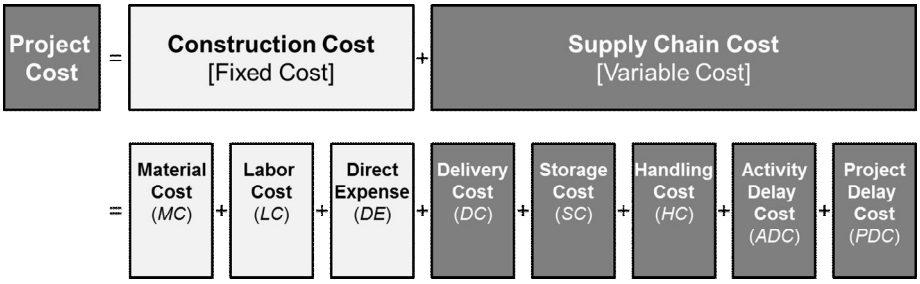


Figure 7-2 Cost model for performance measure of construction supply chain

(1) *Delivery Cost (DC)*: the delivery cost is the cost of the transportation of construction materials from warehouses of suppliers and subcontractors to construction sites. The delivery cost can be defined the sum of the product of the cost of transporting material and the number of times of using transportation vehicles. Both of the variables are dependent on the quantity of the ordered materials. If the order quantity is small, transportation vehicles with a small capacity are used. The cost of transportation vehicles does not increase proportionally with the increase of transportation capacity they have, so that the delivery cost is various depending on the order quantity. In additions, the

number of transportation times is also related to the quantity of the material order. If the quantity of the material order is small, the number of transportation becomes large, on the other hand, the large quantity of the material order make the number of transportation small. Hence, the primary factor affecting the delivery cost can be considered as the quantity of material orders. The equation of the delivery cost (DC) is defined as follows:

$$DC = \sum_{m}^{N_m} \sum_{e}^{N_{tr}} C_{tr(e)}^{m} \cdot N_{tr(e)}^{m} \tag{7-1}$$

where N_m is the number of the types of construction materials; N_{tr} is the number of the types of transportation vehicles $N_{tr(e)}{}^{m}$ is the total number of transportations of the type m material using the type e transportation vehicle; and $C_{tr(e)}{}^{m}$ is the cost of transportations of the type m material using the type e transportation vehicle.

(2) *Handling Cost (HC)*: the Handling Cost is the cost of moving construction materials in construction sites. The handling cost is defined as the following equation

$$HC = N_d \cdot (\sum_{e}^{N_e} C_E + \sum_{u}^{N_e} C_L) \tag{7-2}$$

where N_d is the number of the project overall duration; C_E is the rental cost of the e-th equipment for transporting material package; and C_L is the cost of

the u-th labor for unloading the material packages.

(3) *Storage Cost (SC)*: the storage cost is the cost of rent for additional yard storages outside of construction sites, in order for storing construction materials that cannot be unloaded from transportation vehicles due to full of the capacity of the yard storage space in construction sites. In manufacturing, holding materials, WIPs, and products in their warehouse is regarded as the causes of an expense as to manufacturers have to rent or purchase the storage space. Whereas in construction, yard storage space is given as temporary empty space on a construction site and it does not cause any additional cost during construction. However, it there is no space in the yard storages, contractors have to rent a temporary yard storage and warehouse for those materials, which causes the additional storage cost. Hence, the storage cost is defined as rental cost only for additional storages outside of construction sites and the delivery cost between an additional storage and a construction site. The equation of the storage cost is as follows:

$$SC = \sum_{d}^{N_d}\left(\sum_{i}^{N_{InvE}^{d}} P(i) - A_{ESC}\right)\cdot C_{ERS} + \sum_{d}^{N_d}\left(\sum_{i}^{N_{InvI}^{d}} P(i) - A_{ISC}\right)\cdot C_{IRS} - \sum_{m}^{N_m}\sum_{e}^{N_{tr}} C_{tr}^{k}\cdot N_{tr}^{m} \tag{7-3}$$

where $N_{invE}{}^{d}$ is the number of the occupied inventories in the outdoor storage on the d-th day; $N_{invI}{}^{d}$ is the number of the occupied inventories in the indoor storage on the d-th day; C_{ERS} is the rental cost of the additional outdoor stor-

ages; C_{IRS} is the rental cost of the additional indoor storages; $P_{(i)}$ is the floor area of the *i*-th material packages in the occupied inventory; N_d is the number of the overall duration of the construction project; A_{ESC} is the area of the capacity of the outdoor yard storage; and A_{ISC} is the area of the capacity of the indoor yard storage.

(4) *Activity Delay Cost (ADC)*: The activity delay cost is the cost of construction workers in the idle state that results from material shortage and delivery late, even after a construction activity is executed. The equation of the activity delay cost is as follows:

$$ADC = \sum_{a}^{N_a} D_{de}^{A(\mathrm{a})} \cdot LC^{A(\mathrm{a})} / D_{act}^{A(\mathrm{a})} \tag{7-4}$$

where N_a is the total number of the construction activity; $LC^{A(a)}$ is the cost of the labors for the activity of the type *A(a)*; D_{de} is the duration of delays of the activity of the type *A(a)* due to material shortages; and D_{act} is the duration of the planned activity *A(a)*.

(5) *Project Delay Cost (PDC)*: The project cost represents the cost in terms of the project delay. When the delays of construction projects are caused due to poor management of contractors, owners of construction projects have the right to claim compensation of financial damages from the delays based on liquidated damages clause in contracts.in other words, the loss resulting from

delay days as to contractor's managerial mistakes becomes the range of compensation. For example, contractors have to compensate a loss with regard to delays due to material shortages, when these material shortages occur within the predictable and controllable range of contractors. The equation of the project delay cost (PDC) is defined as follows:

$$PDC = D_{proj} \cdot r_{LD} \cdot C_{proj} \tag{7-5}$$

where D_{proj} is the number of days of the overall delays of the construction project; r_{LD} is the rate of the liquidated damages contracted for the construction project; and C_{proj} is the total cost of the construction project.

7.2.3 Input and Output Data of Simulation Model

Figure 7-3 illustrate the input and output data of the simulation model.

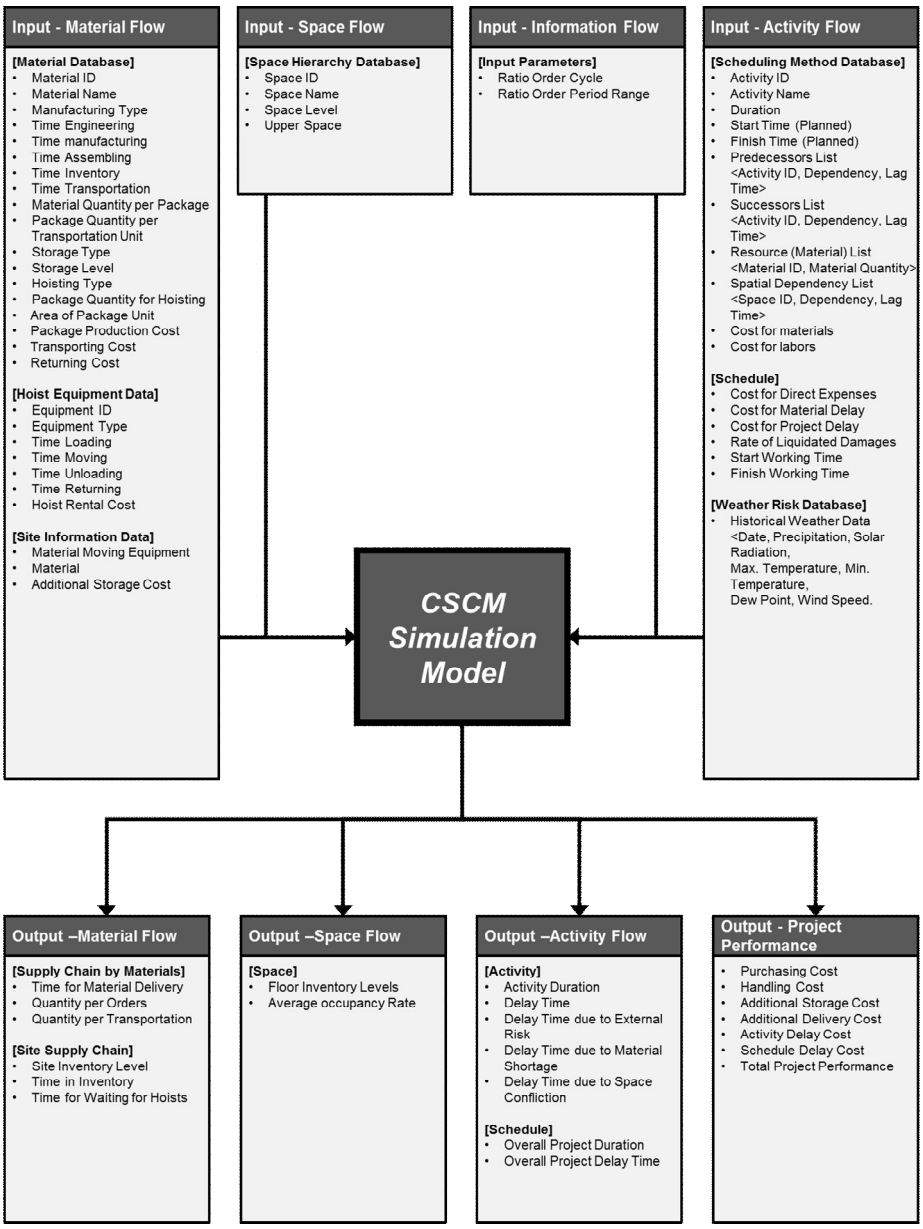


Figure 7-3 Input and output data of construction supply chain simulation model

7.3 Simulation Experiments and Results

7.3.1 Experiment Descriptions

Contractors may have to conduct construction projects in unfamiliar places and newly organize supply chains with suppliers and sub-contractors that they have never worked together. This situation make contractors face risks and uncertainty due to the lack of information on organizations of supply chain and environment surrounding construction projects. As mentioned before, contractor's strategies on the inventory level does not have a simple linear relationship with the performance of construction projects, as the complex behaviors of construction supply chains. Furthermore, there is the possibility that the relationship between them are changed, because the complex behaviors of system components are vulnerable to external risk factors. Here, using the simulation model of construction supply chains, simulation experiments are designed in order to analyze how the external risks factors affect the relationship of the inventory level and the performance of construction projects.

First, the sensitivity analysis are conducted to observe the variation of the relationship of the inventory level and the project's performance according to the increase of the probability of risk factors. Secondly, the patterns of elements of the cost model are analyzed to examine which elements dominantly affect the performance of construction projects.

7.3.2 Input data Descriptions

Simulation experiments in this research are conducted using the actual high-rise building construction project in Chapter 3~5. The input database of the material flow model includes the bill of quantity (BOQ) documents, site information, material transportation equipment and hoisting equipment are the same to those in Chapter 3. For the activity flow model, the historical weather data, non-working criteria, and construction schedule data in Chapter 4 are employed. As to the space flow model, the database of the space hierarchical structure and space creation state in Chapter 5 is also utilized for the experiments.

7.3.3 Simulation Results

Analysis 1: Effect of Construction and Material Supply Risk Factors on the Relationship of Inventory Level and Construction Duration

(a) Result 1-1: Variation of Relationship of Inventory Level and Construction Duration according to Material Supply Risk Events and Construction Schedule Risk Events

Firstly, it was examined how much the material supply risks influence the relationship of the construction duration and the number of days when materials have to be delivered earlier than the execution of construction ac-

tivities (i.e., the number of days before construction). The variation of construction durations according to the extent of the material supply risks is illustrated In Figure 7-4. According to the decrease of the number of days before construction, the inventory level of construction sites become smaller because the storage times of materials are shorten, conversely, as the number of days before construction increases, the inventory level and safety inventory increase.

In most cases of material supply risks, the project durations are significantly higher when the number of days before construction is one (i.e., just-in-time method). If the number of the days increases, the construction duration decreases and shows the minimum values in the range of 2~12 days. After passing through the minimum values of the construction durations, they return to increase slowly. These patterns appear similarly in all the cases of the material supply risks, while the range of fluctuations between the one day after delivery and minimum point become larger with the increase of the material supply risks,. From the simulation results, it can be interpreted that the material supply strategies with the less inventory level are vulnerable to material supply risks that directly lead to material shortages. Therefore, the just-in-time method does not ensure the best performance. In addition, in the case of the simulation experiment with no material supply risks (black bold line), the just-in-time method did not show the better performance. This result can be considered as the proof that the complexity that results from the resource-limited conditions cause interruption to material supply process and

make an adverse effect on the project's performance.

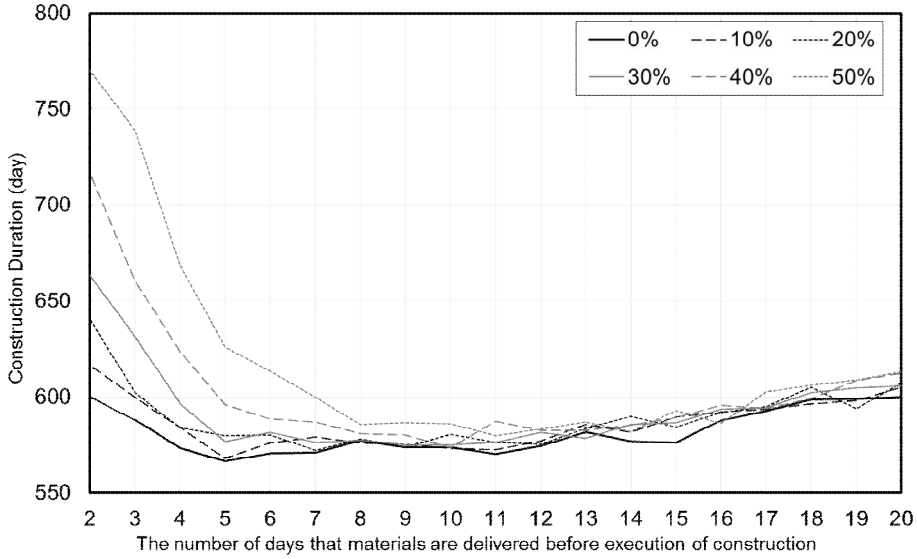


Figure 7-4 Influence of material supply risks on the relationship between the inventory level and construction duration

(b) Result 1-2: Variation of Relationship of Inventory Level and Construction Duration according to Construction Risk Events

In the second place, the impact of construction schedule risks on the relationship between the inventory level and construction duration is examined. As shown in Figure 7-5, with the increase of the probability that delays of the construction activities occur, overall construction duration is also increase. However, the curved pattern shown in the relationship of inventory levels and construction duration disappeared and become a plat. This result suggests that the schedule delays countervail the negative effect due to the

small inventory level, which is considered as the primary cause of the non-linear pattern, because schedule delays perform a role as a time buffer to increase the resource availability by slowing construction process as well as material supply process.

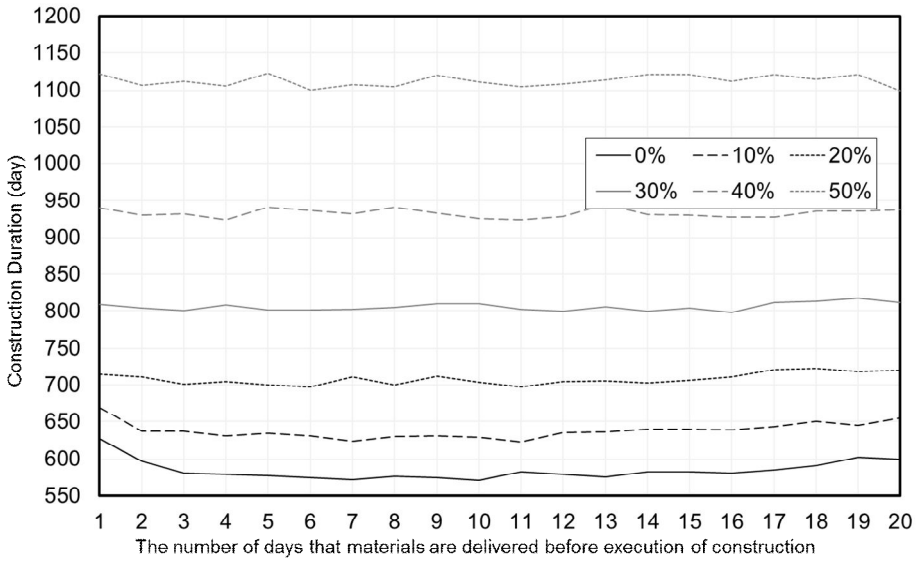


Figure 7-5 Influence of construction schedule risks on the relationship between the inventory level and construction duration

Analysis 2: Variation of Relationship of Inventory Level and Project Cost according to Material Supply Risk Events and Construction Schedule Risk Events

This analysis were conducted to investigate how the relationship of the inventory level and project cost are changed according to the extent of the material supply risks. In this analysis, the variation of the project cost is as-

sociated with the supply chain cost, particularly regarding delivery cost, storage cost, and project delay cost. On the other hand, the construction cost and two cost elements involved in the supply chain cost, namely holding cost and activity delay cost, are assumed constant.

(a) Result 2-1: Variation of Relationship of Inventory Level and Project Cost according to Material Supply Risk Events

Figure 7-6 illustrates the variation of the relationship of the inventory level and project cost according to material supply risks. The pattern of the project cost change smoothly in the specific ranges, while, if the inventory level is beyond the bounds, the project cost sharply increases. A steep increase pattern of project cost can be considered due to the project delay cost (Figure 7-7c) that are incurred when the overall construction duration exceeds the due date of completion. Excluding the effect of the project delay cost, similarly to the relationship of the inventory level and overall construction duration, the pattern of project cost exhibits the maximum cost when the inventory level is the smallest, while the minimum project cost are shown if the inventory level is set up larger than that. However, these variations of the project cost resulting from the delivery cost and storage cost (Figure 7-7a and 7b) is so small in comparison with the whole project cost (<0.1%). Therefore, in making a decision on the inventory level, the most significant element to be considered is construction duration causing the project delay cost, and the inventory level should be set up for construction schedule not

to pass the contract due date. However, the range of the inventory level not to be overdue varies depending on the material supply risks. The larger material supply risk is, the smaller the width of the range is. Therefore, the inventory level should be determined in consideration of the construction duration that is largely affected by the complex behaviors of component of the construction supply chain systems.

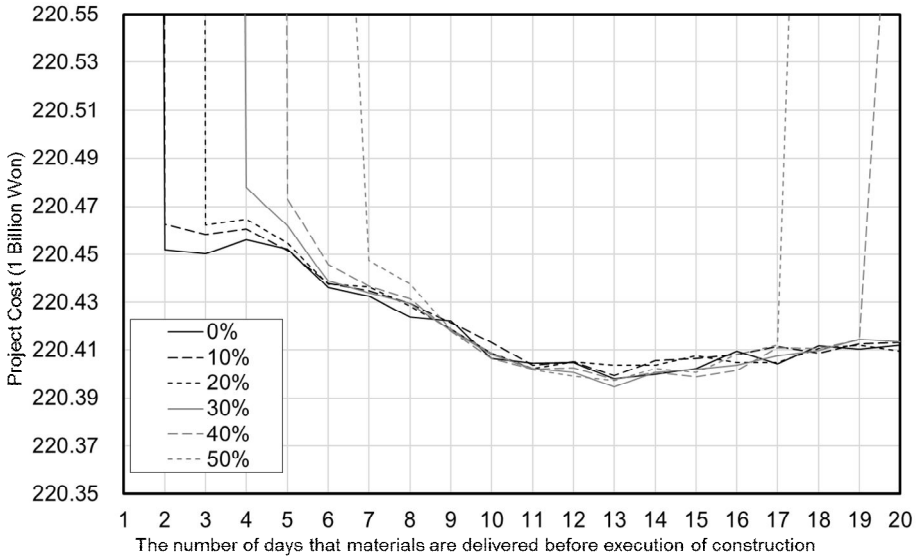


Figure 7-6 Variation of relationship of inventory level and project cost according to material supply risk events

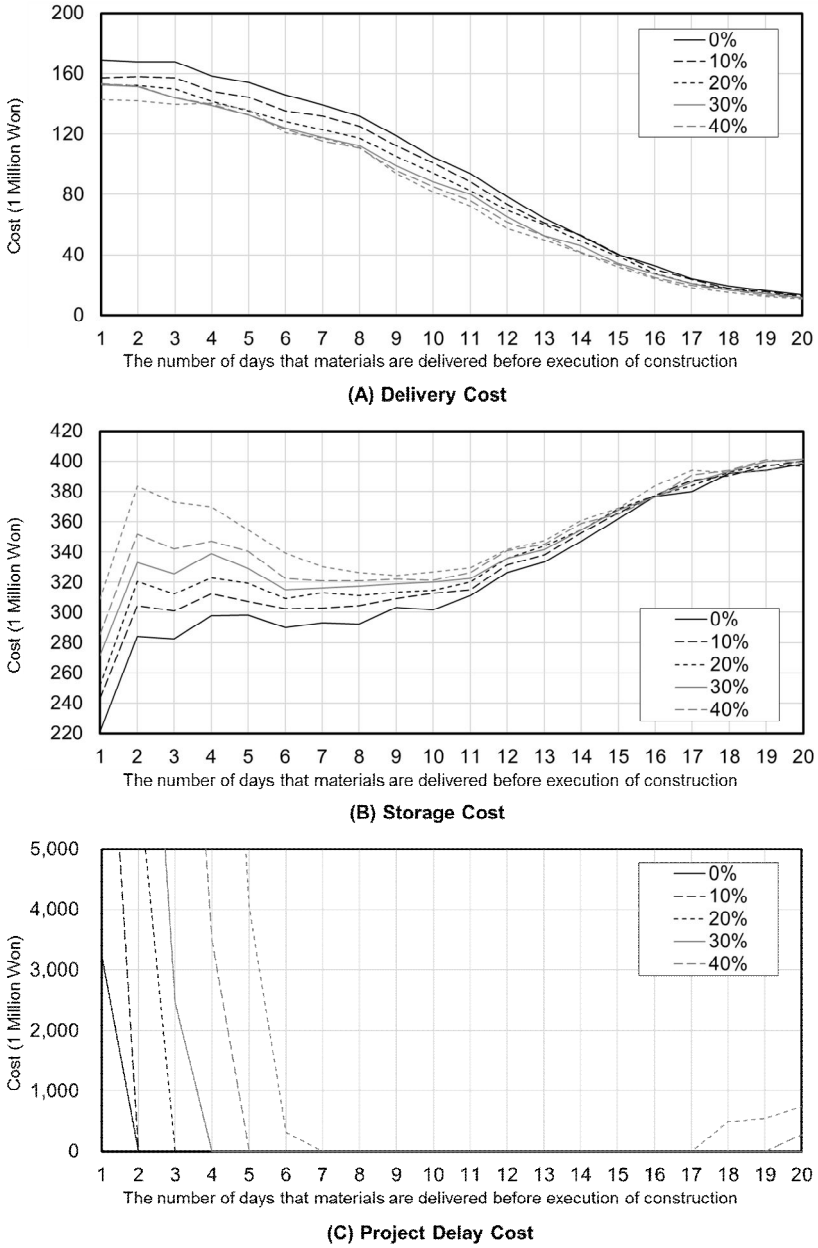


Figure 7-7 Variation of relationship of inventory level and delivery, storage, project delay cost according to material supply risk events

(b) Result 2-2: Variation of Relationship of Inventory Level and Project Cost according to Construction Risk Events

Figure 7-8 shows how the Construction Risk events influence the pattern of the relationship of the inventory level and project cost. As mentioned before, the most dominant factors of the project cost is the construction duration, which shows the plat pattern regardless of the inventory level. Therefore, the variation of the patterns according to the schedule risks are also plat similarly to the patterns of the inventory level and overall construction duration in Figure 7-5.

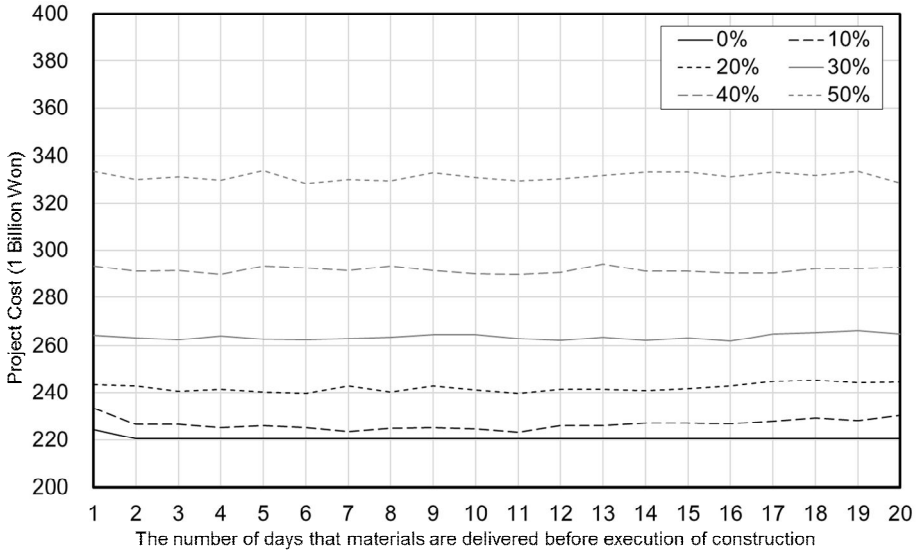


Figure 7-8 Variation of relationship of inventory level and project cost according to construction schedule risk events

7.4 Discussions

Construction projects are systems that are comprised of components whose behaviors are interactive and dynamic. Construction projects are affected by various external risk factors, and these risk factors exist differently by location of the project and have a different effect on the construction projects. Individual components of construction projects can exhibit dissimilar reaction to the external influence factors, because each component has the diversity in materials, resources, and construction methods used for performing its functions. Moreover, the positional characteristics of components, which are given by the position in the network formed by the interdependent relationship between the components (e.g., float time, criticality), influence the process that the impacts of external risks on individual components are diffused to a whole system. Thus, it is not simple to analyze what kind of effects the external influence factors result in on the components of construction projects and the extent to which and how the whole project are affected by these effects.

For these reasons, in a construction management field, there are many previous researches that aims to analyze the relationship of the external risk factors and performance of projects under the assumption that their relationship is linear and the impacts of external risk factors are interdependent on one another. However, as the relationship of them in the real world is more complex than that, it is difficult for contractors to estimate what kind of per-

formance their construction project will exhibit in the given environmental conditions and to determine what kind of strategies they have to choose for maximizing the outcome of their projects.

This research was conducted to investigate how the external risk factors influence to develop contractors' strategies on construction supply chains. For simulating the impact of risk external factors, the delay events in construction and material supply processes are synthetically generated. Moreover, by controlling the extent of the occurrence of these risk events, the variation of the relationship between the inventory level and project performance is examined through the simulation experiments. First, the simulation results show that their relationship are changed according to the extent of the risk events. The inventory level that maximizes the project's performance was changed and the expected value of the project's performance was also changed. Particularly, the delay events on material supply process amplified the change of their patterns, while the risk events on construction activities diminish it. This result can be interpreted that the different types of risk factors have a different effect on the behaviors of construction projects and its component. Hence, when various types of risk events occur simultaneously, the relationship of contractors' strategy and project performance can be changed in a complex way.

In addition, in this research, it is assumed that the risk events occur with the identical probability without regard to type of construction work and ma-

terial. However, in many cases, risk events do not affect construction project bit globally, but locally, due to heterogeneity of construction and material supply processes. Therefore, when contractors develop a strategy such as the inventory level, the risk events affecting construction projects can make the relationship of decision parameters and performance more unpredictable. Hence, it is difficult to analyze the variation of system behaviors using the analytical methods that assume the relationship of system components is constant. Accordingly, it will be necessary to consider the complex behaviors of the components for understanding the relationship between external risk factors and construction supply chain.

7.5 Summary

This research was conducted to extend our understanding by confirming the Hypothesis 5 regarding how external risk factors affect the relationship of the strategies and performance of construction projects. To achieve these goals, the synthetic risk generation models which generate delays in construction and material supply processes are integrated with the simulation models developed in the previous chapters. Moreover, the cost model was developed for measuring the performance of supply chains in the various perspectives as well as an overall duration of construction supply chains. Finally, simulation experiments with real data are carried out in order to examine how the complex behaviors of those models are affected by the exter-

nal risk factors and influence the performance of a whole system.

Through the simulation experiments, in construction supply chains whose components exhibit complex behaviors, the relationship between the decision variables and expected performance is not constant, but variable according to given environmental conditions. In other word, even though the construction projects are technically identical, the risk environment can change the way to find the best strategy as well as the best strategy itself. This can be considered as a result that the behaviors and relationships of components of the construction supply chain are changed by the impact of various types of risk environments. As the existing methods are based on the assumption that the relationship of strategy and project performance is constant and independent of other factors, they can be difficult to explain the behaviors of construction supply chains in the case that construction projects show the complexities. Thus, it should be analyzed by considering the dynamic and interdependent relationship of the components based on the holistic view.

Chapter 8. Conclusions

8.1 Summary of Researches

The main objective of this research is to investigate complex behaviors in supply chains of high-rise building construction projects and their effect on the project's performance. To achieve this objective, I established the five hypotheses based on the perspective of complex system and carried out the five interrelated researches that include the development of simulation models and the simulation experiments using the real-world data in order to confirm these hypotheses. Through the results of the simulation experiments, these studies found that complex behaviors exist within and between processes and cause unpredictable effects on a project-level performance. Summary of the findings and implications of these studies are as follows.

(1) ***Impact of Severe Weather Conditions on Concurrent Construction Process*****:** In concurrent constructions, due to the heterogeneous characteristics and local connectivity of construction activities, severe weather does not have the same effect on all construction activities, however, affects only the relevant activities, which deliver these impacts of the small number of activities related to them in the construction schedule. As a result, severe weather events do not always result in a critical effect on construction schedules, as the state of each activity (e.g., total float) is various and changed dynamical-

ly. Therefore, the process for influence factors, which have a local effect on construction works like severe weather, to affect a whole construction schedule is complex and difficult to explain with the relationship of a part of construction activities and those factors. Thus, for analyzing their impacts, it is significant to consider diverse characteristics and relationship of construction activities as a whole.

(2) ***Interference between Different Material Supply Channels due to Lack of Supply Chain Resources*****:** In a building construction site, due to insufficiency of supply chain resources, different types of material supply process have to share the same resources, and this can result in interferences among these processes, which cause a negative effect on construction works in the form of a material delivery delay. However, these interferences occur irregularly and are difficult to predict, because they occur as a collective result of various types of material supplies, which require a different amount and type of resource and whose period also varies. In addition, the impact of construction works is complex, as a material delivery delay resulting from these interferences has a local effect on a concurrent construction process. Therefore, the effect of these interferences is difficult to estimate based on characteristics of individual material supply processes, while various relationships of those processes have to be considered.

(3) ***Spatial Conflicts between Construction and Material Supply Processes in Allocating Working Space in Buildings:*** *a* material supply process affects

a construction process in the form of material shortage, while a material supply process is generally assumed to be independent from a construction process. In building constructions, however, a material supply process can be affected by a construction process. Due to lack of yard storage space in a building construction site, material packaged stored in yard storages should be transported into the workspace in buildings as soon as possible for avoiding excess inventory. However, work space in buildings is also not enough to cover all of material packages delivered, moreover, area of material storing space can be changed according to characteristics of construction works performed in that space. In this case, the variation of a construction process can cause delays in the process that materials are transported from yard storages to work spaces, and due to lack of the storage space, this can also result in delays of other material supply processes, which have the possibility to cause the variation of a construction process. Then, this process is repeated during construction, the effect both on the performance of construction and material supply process is so complex to explain it with the simple relationship.

(4) ***Impact of Material Supply Strategy on Complex Behaviors in Construction Supply Chain Processes*****:** under resource limited conditions like high-rise building construction, the just-in-time method is considered as one of the most effective methods to minimize on-site resource usages of construction materials. However, this method has the disadvantage that it is vulnerable to external risks because in this method, safety stock that can prevent

material shortage is regarded as waste to be eliminated, so that risks on material supply directly affect a construction process without any buffers. This research revealed that even under the condition that there do not exist external risks, just-in-time can increase negative effects on a construction process, as internal interferences and interactions of components of projects can cause delays in material supply processes and they can lead to negative effects on construction projects in just-in-time. On the other hands, in the case that materials are supplied excessively, overall construction durations also increase, due to increase of the complex behaviors of the project's components.

(5) ***Non-linear and Variable Relationship of Construction Supply Chain and Risk Environment*****:** as performed in the various regions of the world, construction projects have become to face various types of risks. Previous researches that analyze the effect of risk factors on project performance, generally, have assumed that risk factors are independent from one another and the relationship with them is linear and constant. However, a construction project is comprised of interdependent components, whose relationship is possible to change according to risk environments. Therefore, the relationship of risks and project performances is not always constant, but variable depending on a situation.

To summarize these findings, this research reveals that in the system of supply chain, complex behaviors of the system's components can occur at vari-

ous levels and have complex effects on the entire system. These impacts caused by the complex behaviors is difficult to explain with characteristics of individual components, so that it is essential to consider various relationship of components, based on the perspective of complexity.

8.2 Contributions

The research contributed to the body of knowledge by doing the followings.

(1) ***Development of a conceptual framework of construction supply chain management*****:** since the concept of lean manufacturing was introduced to construction industry, many attempts have been made to understand supply chain of construction project as a complex system based on holistic perspectives. Even though these attempts have provide a great insight to understand construction supply chain by considering various types of complex behaviors resulting from interactions within and between flows. However, many of them have focuses on building a theoretical model and made less efforts to find specifically what kind of complex behaviors exist and what kind of effect emerges in a project level. By investigating characteristics of supply chains of high-rise building constructions, this study found four types of flows, which is interdependence with each other and whose complex behaviors affects the project's performance. Based on behaviors of the four flows,

this study proposed a conceptual framework that is useful for analyzing construction and material supply processes in complex system's views.

(2) ***Development of agent-based simulation models for investigating complexities of construction projects*****:** many previous studies on the complexity of construction projects have focused on the development of theoretical frameworks, however, in order to clarify their complex behaviors with an empirical case, this research attempted to develop qualitative models based on the agent-based and discrete-event simulation methods. Particularly, the agent-based simulation method has strong advantages in dealing with complex problems, because this method defines not a process, but behaviors of components, so that researchers are able to examine various types of emerging effects, which it is difficult to predefine in simulation models. The simulation techniques and models developed in this research will be useful to extend our researches on complexity of construction to other types of construction projects, which have their own complex behaviors and relationships.

(3) ***Enhancement of our understanding of complex behaviors of construction supply chain*****:** based on a reductionist approach, many previous studies have still focused on identifying the key components and factors in construction project and their relationship with a project performance. There is no doubt that these previous efforts provide useful insights for understanding complex construction projects and improving their performances. However, this research confirmed the possibility that various types of complex behav-

iors exist in construction projects and they create emergent effects on project performances, which it is difficult to explain based on a reductionist approach. Including the findings from this research, various attempts based on the perspective of complexity will enhance our understanding on construction projects and be helpful to improve project performances.

8.3 Future Researches

Nevertheless, there are still limitations and challenging issues for future researches as follows.

(1) ***Investigating the process that the interaction of components affect the whole system***: this study attempted to demonstrate that interactive behaviors can occur in construction and material supply processes and that those interactive behaviors makes an impact on the project's performance. However, the process that the project-level effect emerged from the interaction of components was not investigated in this study. By tracking the affect transfer process, it will be possible to identify in which conditions amplify or diminish the effect caused by interactions, and findings from this make us to understand how we can control the negative effect emerged from the interactions in construction process.

(2) ***Investigating the effect of decision variables of supply chains on the***

performance of construction project: this study focused on understanding the relationship between the material order quantity and the performance. However, there are large numbers of decision variables, which have to be considered for organizing supply chains and in planning construction processes. Those variables such as building design, construction method, and the number and type of transportation and hoisting equipment can amplify or diminish the interactive behaviors of flows and their emerging effect on the project's performance. In consideration of feedback structure of supply chains, particularly, time buffer in construction schedule have the possibility to influence the complex behaviors of material supply and construction process. Those further studies will deepen our understanding on how construction managers should control the complexities.

(3) ***Enhancing the validity of the simulation model and generalizing findings of complex behaviors***: in this study, the simulation experiments are conducted using the data from the single case of the high-rise building construction. Those simulation experiments can be considered as sufficient to confirm the possibility of complex behaviors under resource-limited conditions, however, they have limitations in providing more reliable result value and in generalizing the pattern of emerged complex behaviors. By applying the proposed model and method to many construction cases, deeper understanding on supply chain and construction management will be obtained.

(4) ***Providing viable alternatives to decision makers regarding supply chain***

and construction project management: one of the strength of simulation methods is that they can make an answer to what-if problems. After the developed models obtain the validity enough to provide viable outcome values, the models can produce more benefits to decision makers by providing practicable alternatives. Simulation-based optimization method, which incorporate simulation model and non-linear problem solver such as Genetic Algorithm, have the large possibility to find the optimal solution under the condition, where many decision variables interact to each other.

(5) ***Complex problems regarding autonomously behaving organizations in supply chain***: complex behaviors analyzed in this study focus on the interaction of material supply and construction process, which are controlled with contractors' strategy for material order quantity. However, in the real construction projects, various participants that have different roles and responsibilities as well as different purposes operate a supply chain. Project performance can be affected by those participants' strategies, which are changed depending on the variation of environment such as chances for maximizing profits and risks causing loss. In this context, various complex behaviors at the project level can emerge from interactive behaviors of autonomous participants. To analyze their complex behaviors will broaden our understanding of supply chain management and increase chance to maximizing the performance of construction projects.

(6) ***Broadening the application of the proposed method to various types of***

construction projects: the conceptual framework and simulation models developed in this study aims to represent the complex behaviors in supply chains of building constructions. All types of constructions such as highway, tunnel, bridge and plant constructions have own distinctive characteristics in working environment concerning material supply and construction process. By applying the conceptual framework to various types of construction projects, characteristics by construction type will be more differentiated and, conversely, the common feature of constructions will become more explicit.

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Appendix 1: Structure and Components of Construction Supply Chain Management (CSCM) Simulation Models and Java Codes of Key Functions

The construction supply chain simulation model was developed using the Java-based multi-method simulation tool, Anylogic 7.1 University. The structure and component of simulation models are provided here in the form of picture and Java code and I hope that they can help the readers of this dissertation to deepening their understanding of this simulation model. Unfortunately, however, it is difficult to provide all of information on the simulation models due to license problem and space limits in this dissertation.

1-A. Structure of CSCM Simulation Model

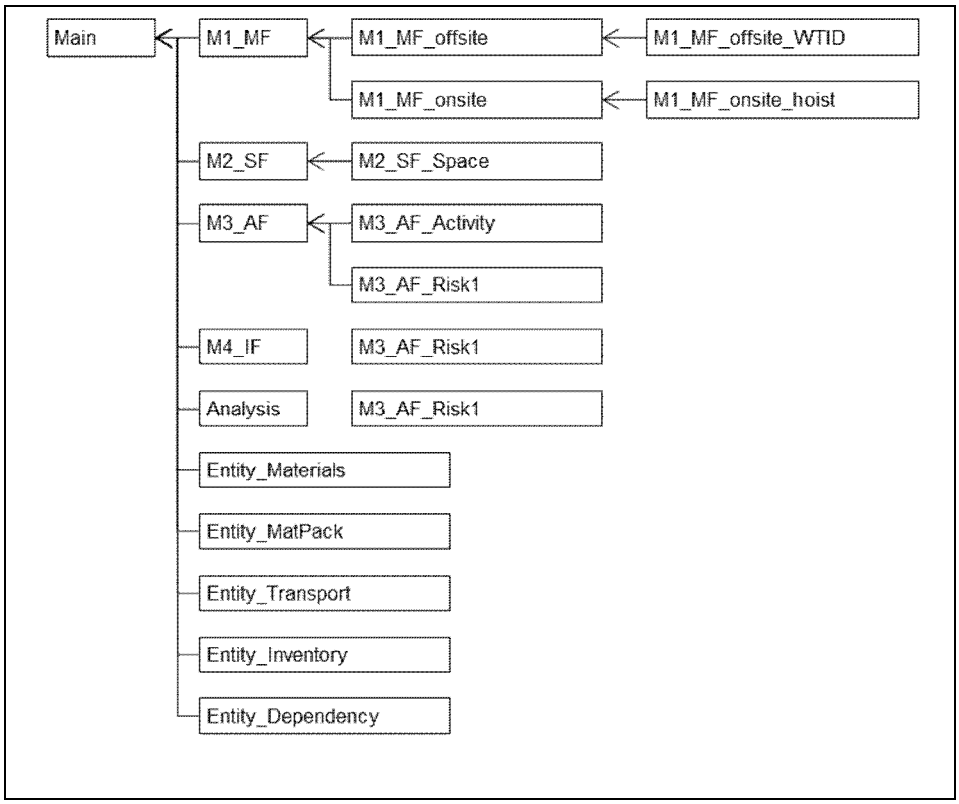

Figure 1-A-1. Structure of classes of CSCM simulation model

1-B. Class of CSCM Simulation Model

■ Class of Material Flow Model <Main>

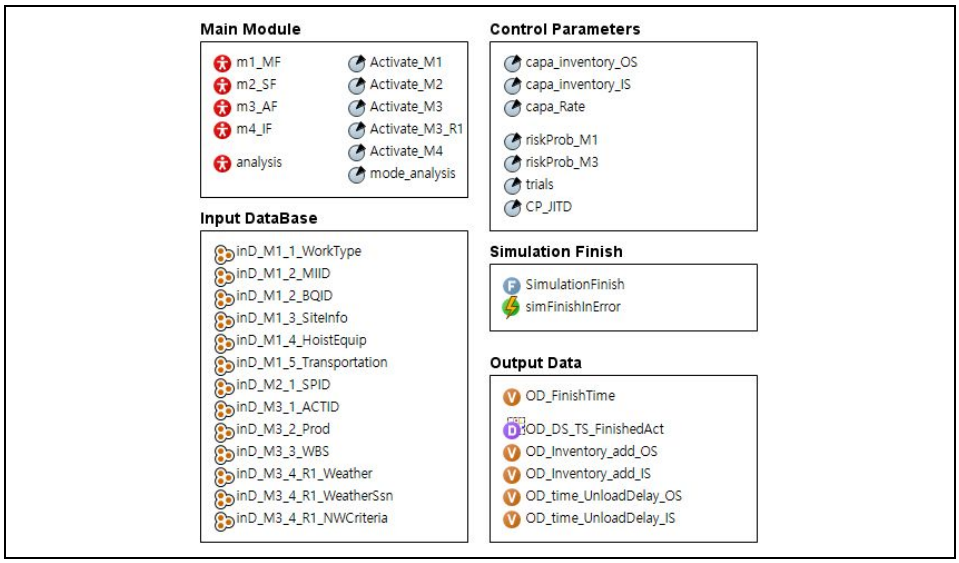

Figure 1-B-1. Picture of < Main > class in Anylogic 7.1

■ Class of Material Flow Model <M1_MF>

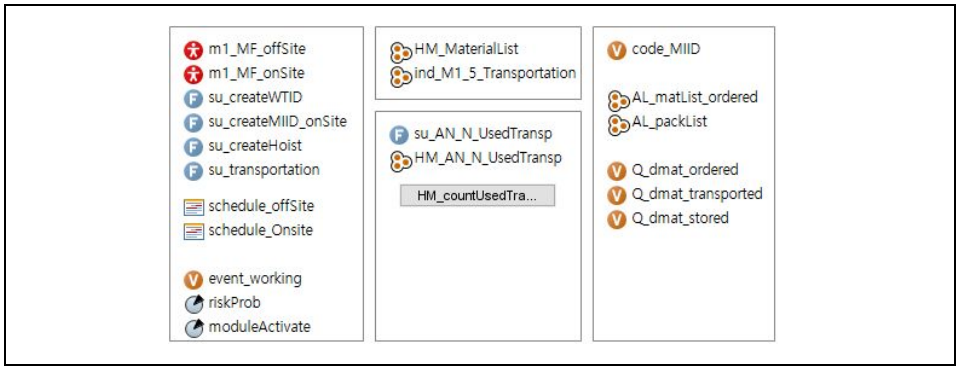

Figure 1-B-2. Picture of <M1_MF> class in Anylogic 7.1

■ **Class of Off-Site Material Flow Model <M1_MF_offSite>**

Figure 1-B-3. Picture of < M1_MF_offSite > class in Anylogic 7.1

■ **Class of Off-site Material Flow Model <M1_MF_offSite_WTID>**

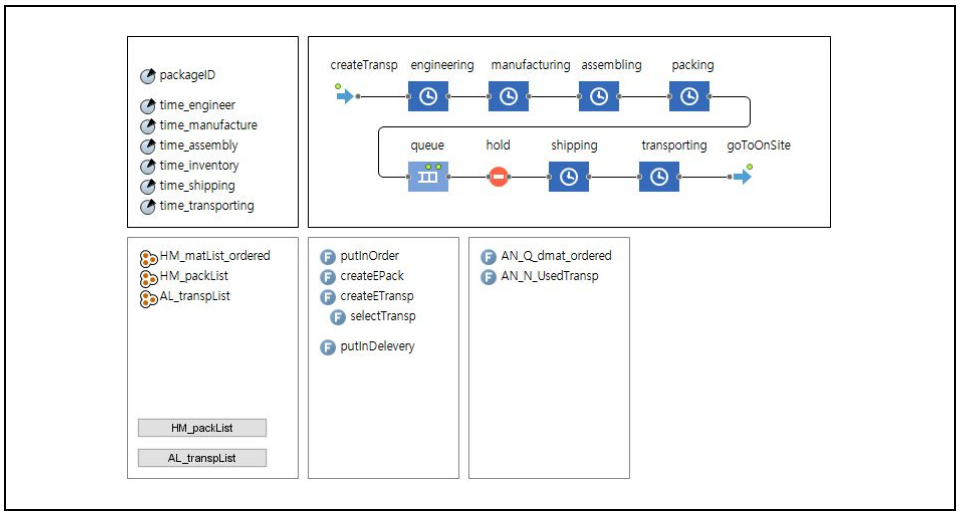

Figure 1-B-4. Picture of <M1_MF_offSite_WTID> class in Anylogic 7.1

// Function of [createETransp]: creating entity of transportation vehicle

```
Public void createETransp()
{
     Iterator iter = HM_packList.keySet().iterator();

     while(iter.hasNext()){
          InD_M1_2_MIID m1_miid = (InD_M1_2_MIID)iter.next();

          // indentify num of pack of m1_miid
          ArrayList<Entity_MatPack> packList   = HM_packList.get(m1_miid);
          int packNum = packList.size();

          // identify num of pack in entity_transportation
          ArrayList<Integer> capaPackArray = function(m1_miid);

          int maxNumTransp = capaPackArray.get(capaPackArray.size()-1);

          while(packNum>0){

               if(packNum > maxNumTransp){
                         //traceln("A "+packList.size());
                    // 1 Select Transportation
                    InD_M1_5_Transportation ind_transp =
m1_MF.ind_M1_5_Transportation.get(m1_MF.ind_M1_5_Transportation.size()-1);

                    // 2 Prepare Transportation
                    Entity_Transport transp = new Entity_Transport();
                    transp.ind_transp    = ind_transp;
                    transp.m1_wtid       = ind_wtid;
                    transp.ind_miid      = m1_miid;
                    AL_transpList.add(transp);

                    // 3 Shippiing on Transportation
                    for(int i=0; i<maxNumTransp; i++){
                         transp.mpackListInTr.add(packList.remove(0));
                         packNum--;
                    }
               }
               else{

                    // 1. Select Transportation
                    int numShip = 0;
                    InD_M1_5_Transportation ind_transp = null;
                    Loop:
                    for(int i=m1_MF.ind_M1_5_Transportation.size(); i>0; i--){
                         if(capaPackArray.get(i-1) >= packNum){
                              ind_transp = m1_MF.ind_M1_5_Transportation.get(i-1);
                              numShip    = capaPackArray.get(i-1);
                         }
                         else{
                              break Loop;
                         }
```

```
                    }

                    // 2. Prepare Transportation
                    Entity_Transport transp = new Entity_Transport();
                    transp.ind_transp    = ind_transp;
                    transp.m1_wtid       = ind_wtid;
                    transp.ind_miid      = m1_miid;
                    AL_transpList.add(transp);

                    // 3. Shippiing on Transportation
                    for(int i=0; i<packList.size(); i++){

                         transp.mpackListInTr.add(packList.remove(0));
                         packNum--;
                    }
               }
          }
     }

     HM_packList.clear();
}
```

// Function of [setTransp]: selecting type of transportation vehicles

```
Public ArrayList<Integer> createETransp()
{
          ArrayList<Integer> capaPackArray = new ArrayList<Integer>();

     double pWeight  = miid.PackWeight;
     double pLength  = miid.PackLength;
     double pWidth   = miid.PackWidth;



     for(InD_M1_5_Transportation m1_transp:m1_MF.ind_M1_5_Transportation){

          double tWeight  = m1_transp.TRWeight;
          double tLength  = m1_transp.TRLength;
          double tWidth   = m1_transp.TRWidth;

          // capa by weight
          int wPackNum = (int)Math.floor(tWeight/pWeight);

          // capa by area
          int aPackNumWidth    = (int)Math.floor(tLength/pLength);
          int aPackNumLeng     = (int)Math.floor(tWidth/pWidth);

          int aPackNum = aPackNumWidth*aPackNumLeng*miid.InventoryPile;
```

```
            if(wPackNum<aPackNum)
                capaPackArray.add(wPackNum);
            else
                capaPackArray.add(aPackNum);

        }
        return capaPackArray;
}
```

■ Class of On-site Material Flow Model <M1_MF_onsite>

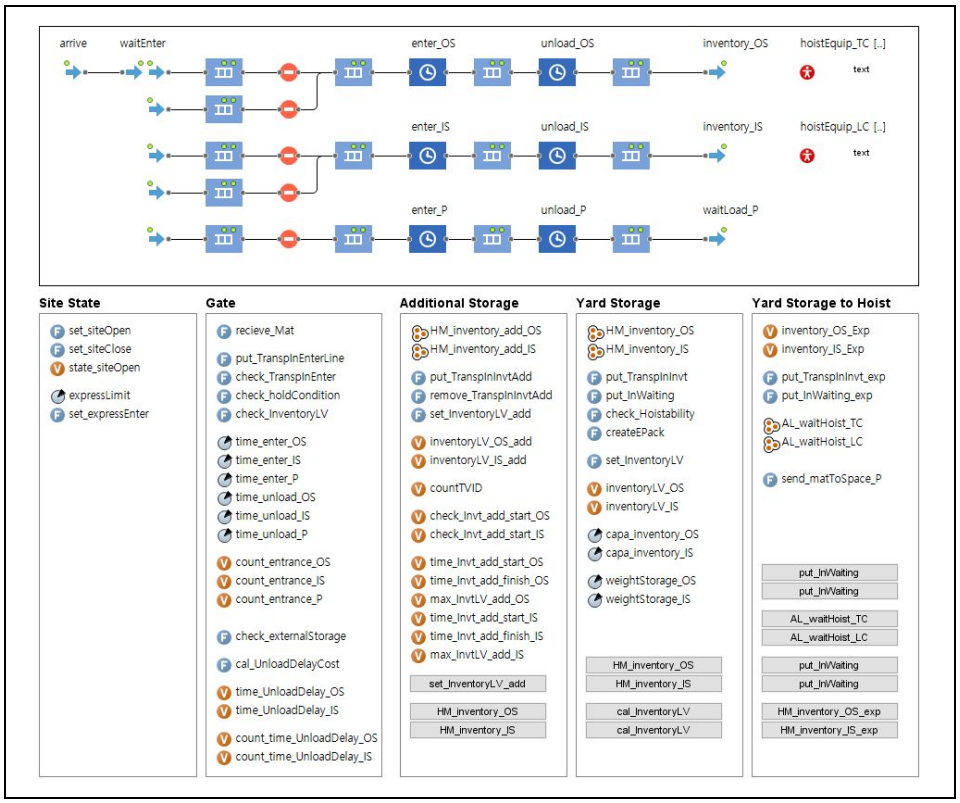

Figure 1-B-5. Picture of <M1_MF_onsite> class in Anylogic 7.1

// Function of [put_TranspInEnterLine]: Controlling transportation vehicles to enter the construction site

```
Public void put_TranspInEnterLine (Entity_Transport transp)
{
     int storageType = transp.ind_miid.storageType;
     ArrayList<M3_AF_Activity> actList = new ArrayList<M3_AF_Activity>();

     boolean check_quickDelivery = false;
     boolean check_fullInventory = false;

     // check_fullInventory
     int type = transp.ind_miid.hoistType;
     if(type == 1){
          if(inventoryLV_OS >= capa_inventory_OS) check_fullInventory = true;
     }
     else if(type ==2){
          if(inventoryLV_IS >= capa_inventory_IS) check_fullInventory = true;
     }

     if(check_fullInventory){
          for(Entity_MatPack mpack:transp.mpackListInTr){
               for(Entity_Material dmat:mpack.matListInPack){
                    if(!actList.contains(dmat.m3_act)){
                         actList.add(dmat.m3_act);
                    }
               }
          }
          for(M3_AF_Activity m3_act:actList){
               if(m3_AF.AL_M3_Act_Stort.contains(m3_act)){
                    check_quickDelivery =true;
                    break;
               }
          }
     }

     if(check_quickDelivery){
          if(storageType == 1)      waitEnter_exp_ent1.take(transp);
          else if(storageType == 2) waitEnter_exp_ent2.take(transp);
          else if(storageType == 0) waitEnter_ent0.take(transp);
     }
     else{
          if(storageType == 1)      waitEnter_ent1.take(transp);
          else if(storageType == 2) waitEnter_ent2.take(transp);
          else if(storageType == 0) waitEnter_ent0.take(transp);
     }
}
```

// Function of [put_TranspInInvt]: transforming from entity of transportation vehicle to entity of inventory

```
Public void TranspInInvt(Entity_Transport transp, int type)
{
     transp.TVID = countTVID;
     countTVID++;

     ArrayList<Entity_Material> dmatList = new ArrayList<Entity_Material>();

     // [1] Extracting Entity_Material
     ArrayList<Entity_MatPack> mpackListInTr = transp.mpackListInTr;
     for(Entity_MatPack mpack:mpackListInTr){
          dmatList.addAll(mpack.matListInPack);
     }

     // [2] Identify Entity_Inventory
     Entity_Inventory inventory;
     if(type==1){
          if(HM_inventory_add_OS.containsKey(transp.ind_miid))
               inventory = HM_inventory_add_OS.get(transp.ind_miid);
          else{
               inventory = new Entity_Inventory();
               inventory.ind_miid        = transp.ind_miid;
               HM_inventory_add_OS.put(inventory.ind_miid, inventory);
          }
     }
     else if(type==2){
          if(HM_inventory_add_IS.containsKey(transp.ind_miid))
               inventory = HM_inventory_add_IS.get(transp.ind_miid);
          else{
               inventory = new Entity_Inventory();
               inventory.ind_miid        = transp.ind_miid;
               HM_inventory_add_IS.put(inventory.ind_miid, inventory);
          }
     }
     else{
          inventory = new Entity_Inventory();
          traceln("FatalError[transpInInventory(2)]");
     }

     // [3] Put dmat in inventory
     for(int i=0; i<dmatList.size(); i++){
          Entity_Material dmat = dmatList.get(i);
          inventory.addInventory_add(dmat);
     }

     // [4] Calculation Inventory Level
     inventory.calInventoryLV();
     set_InventoryLV_add(type);
}
```

■ Class of Hoisting Equipment Agent <M1_MF_onsite_hoist>

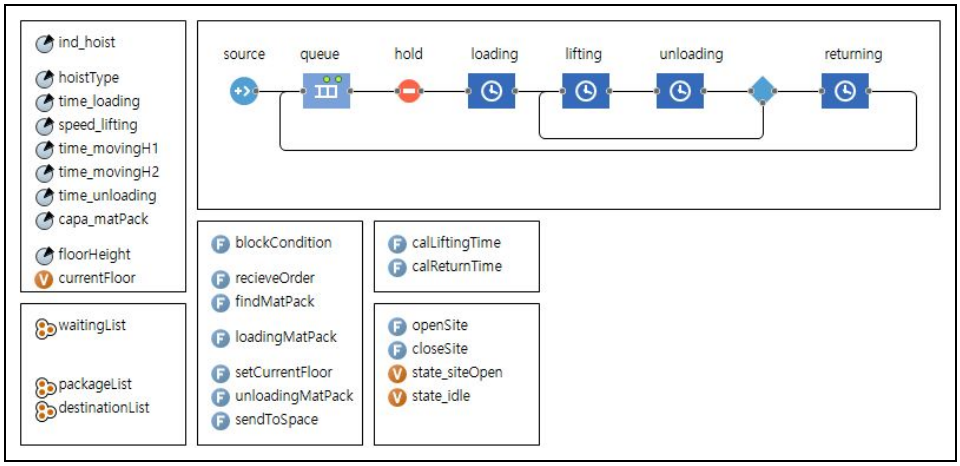

Figure 1-B-6. Picture of <M1_MF_onsite_hoist> class in Anylogic 7.1

// Function of [loadingMatPack]: loading material package

```
Public void loadingMatPack ()
{
     for(Entity_MatPack mpack:waitingList){

          // [1] put mpack in package list
          packageList.add(mpack);

          // [2] set inventory level
          for(Entity_Material dmat:mpack.matListInPack){
               if(dmat.expressDelivery){
                    mpack.inv.removeHoistedMat(dmat);

                    mpack.inv.calCrtQmat();
                    mpack.inv.calCrtQPack();
                    mpack.inv.calInventoryLV();

                    if(mpack.inv.crtQMat == 0.0){
                         if(hoistType == 1 )
                              m1_MF_onSite.inventory_OS_Exp = null;
                         else if(hoistType == 2)
                              m1_MF_onSite.inventory_IS_Exp = null;

                         m1_MF_onSite.check_holdCondition(hoistType);
                    }
               }
```

```
                else mpack.inv.removeHoistedMat(dmat);
            }

            // [3] set up destination list
            int destination =  mpack.matListInPack.get(0).m3_act.ind_actid.SPL3;
            if(destinationList.isEmpty()){
                destinationList.add(destination);
            }
            else{
                boolean checkAdd = false;
                Loop:
                for(int i=0; i<destinationList.size(); i++){
                    if(destination == destinationList.get(i)){
                        checkAdd = true;
                        break Loop;
                    }
                    if(destination < destinationList.get(i)){
                        destinationList.add(i, destination);
                        checkAdd = true;
                        break Loop;
                    }
                }
                if(!checkAdd)
                    destinationList.add(destination);
            }

        }

        waitingList.clear();
        m1_MF_onSite.set_InventoryLV(hoistType); }
```

// Function of [unloadingMatPack]: unloading material package

```
Public void unloadingMatPack()
{
    ArrayList<Entity_MatPack> unloadList = new ArrayList<Entity_MatPack>();

    for(Entity_MatPack mpack:packageList){
        if(currentFloor == mpack.matListInPack.get(0).m3_act.ind_actid.SPL3)
            unloadList.add(mpack);
    }

    // [Analysis] leadtime - HoistedToArrived
    if(main.mode_analysis){
        if(hoistType == 1){
            for(Entity_MatPack mpack:packageList){
                m1_MF_onSite.AN_AL_D_LT_HoistArrive_OS.add(time()-mpack.leadTime);
                m1_MF_onSite.AN_AL_D_LT_Total_OS.add(time()-mpack.leadTime_total);
                mpack.leadTime = time();
```

```
                }
            }
            else if(hoistType == 2){
                for(Entity_MatPack mpack:packageList){
                    m1_MF_onSite.AN_AL_D_LT_HoistArrive_IS.add(time()-mpack.leadTime);
                    m1_MF_onSite.AN_AL_D_LT_Total_IS.add(time()-mpack.leadTime_total);
                    mpack.leadTime = time();
                }
            }
        }

        for(Entity_MatPack mpack:unloadList){
            packageList.remove(mpack);

            sendToSpace(mpack);
        }
}
```

// Function of [calLiftingTime]: calculating lifting time

```
Public double calLiftingTime()
{
            double liftingTime = 0.0;

        if(!destinationList.isEmpty()){
            int destFloor = destinationList.get(0);
            double liftDistance = (destFloor-currentFloor)*floorHeight;

            if(liftDistance>0)
                liftingTime = liftDistance/speed_lifting;
            else{
            }
        }
        else traceln("FatalError[calLiftingTime]: No Destination in list");

        return liftingTime;
}
```

■ **Class of Space Flow Simulation Model <M2_SF_Space>**

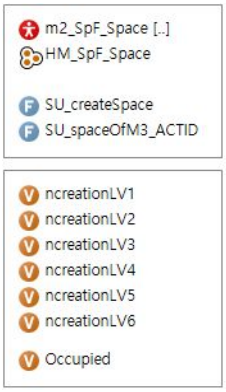

Figure 1-B-7. Picture of <M2_SF_Space> class in Anylogic 7.1

■ **Class of Space Agent <M2_SF_Space>**

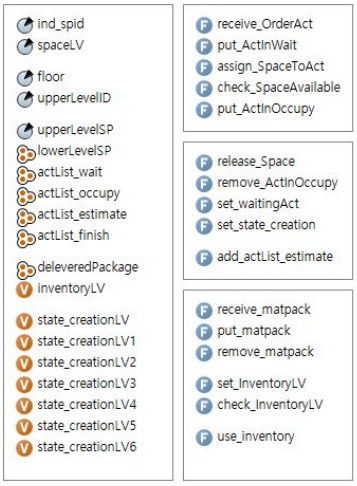

Figure 1-B-8. Picture of <M2_SF_Space> class in Anylogic 7.1

// Function of [check_SpaceAvailable]: checking space availability considering relevant space agent in space hierarchy structure

```
Public boolean check_SpaceAvailable (M3_AF_Activity m3_act)
{
     m2_SF.numExec_check_SpaceAvailable++;

     // check actList_estimate
     boolean checkAvailable = true;

     if(m3_act != null){
          int index_m3_act = actList_estimate.indexOf(m3_act);
          Loop:
          for(int i=0; i<index_m3_act; i++){
               M3_AF_Activity m3_act_predAct = actList_estimate.get(i);
               if(!m3_act_predAct.event_start){
                    checkAvailable = false;
                    break Loop;
               }
          }
     }

     // check lowerLevelSP
     if(checkAvailable && actList_occupy.isEmpty()){
          for(M2_SF_Space m2_space:lowerLevelSP){
               if(!m2_space.check_SpaceAvailable(m3_act)){
                    checkAvailable = false;
                    traceln("lowerLevelSP");
                    break;
               }
          }
     }
     else{
          checkAvailable = false;
     }

     return checkAvailable;
}
```

// Function of [set_state_creation]: setting space creation state of all relevant space agent in space hierarchy structure

```
Public void set_state_creation (M3_AF_Activity m3_act)
{
     //traceln("# removeActInOccupy \t"+time());
     m2_SF.numExec_set_state_creation++;

     state_creationLV = m3_act.SPCreationLV;
```

```
/* if(!state_creationLV5 && state_creationLV6){
     traceln(">>>m3_act: "+m3_act.WBS);
     getEngine().pause();
     viewArea.navigateTo();
}*/
boolean checkChange = false;

if(state_creationLV==1 && !state_creationLV1){
     if(!state_creationLV1 && spaceLV ==5)
          m2_SF.ncreationLV1++;
     state_creationLV1 = true;
     checkChange = true;
}
else if(state_creationLV==2 && !state_creationLV2){
     if(!state_creationLV2 && spaceLV ==5)
          m2_SF.ncreationLV2++;
     state_creationLV2 =  true;
     checkChange = true;
}
else if(state_creationLV==3 && !state_creationLV3){
     if(!state_creationLV3 && spaceLV ==5)
          m2_SF.ncreationLV3++;
     state_creationLV3 =  true;
     checkChange = true;
}
else if(state_creationLV==4 && !state_creationLV4){
     if(!state_creationLV4 && spaceLV ==5)
          m2_SF.ncreationLV4++;
     state_creationLV4 =  true;
     checkChange = true;
}
else if(state_creationLV==5 && !state_creationLV5){
     if(!state_creationLV5 && spaceLV ==5)
          m2_SF.ncreationLV5++;
     state_creationLV5 =  true;
     checkChange = true;
}
else if(state_creationLV==6 && !state_creationLV6){
     if(!state_creationLV6 && spaceLV ==5)
          m2_SF.ncreationLV6++;
     state_creationLV6 =  true;
     checkChange = true;
}

if(checkChange){
     for(M2_SF_Space m2_space:lowerLevelSP){
          m2_space.set_state_creation((m3_act));
     }
} }
```

■ Class of Activity Agent <M3_AF >

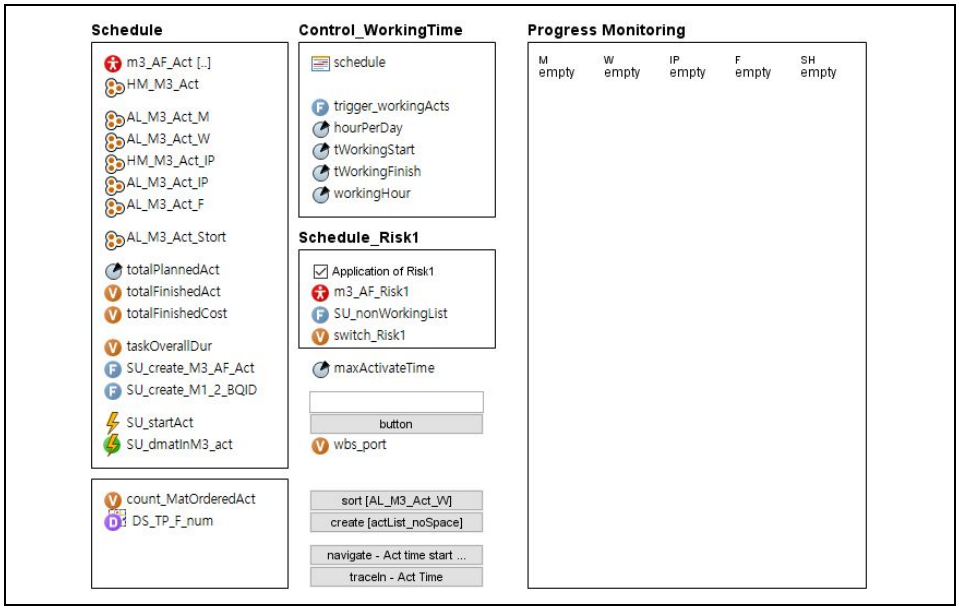

Figure 1-B-9. Picture of <M3_AF > class in Anylogic 7.1

// Function of [SU_create_M3_AF_Act]: creating activity agents and their connectivity based on construction schedule

```
Public void set_Duration ()
{
     // Create M3_AF_Activity
     Iterator iter = get_Main().inD_M3_1_ACTID.keySet().iterator();
     while(iter.hasNext()){
          InD_M3_1_ACTID ind_actid = get_Main().inD_M3_1_ACTID.get(iter.next());

          if(ind_actid.WBSLv == 4){
               M3_AF_Activity m3_act = this.add_m3_AF_Act();

               m3_act.ind_actid          = ind_actid;
               m3_act.WBS           = ind_actid.WBS;
               m3_act.WBSLv         = ind_actid.WBSLv;
               m3_act.SPCreationLV = ind_actid.SPCreationLV;

               //LHM Save
               HM_M3_Act.put(m3_act.WBS, m3_act);
          }
```

```
}

// Set Dependency
iter = get_Main().inD_M3_1_ACTID.keySet().iterator();
while(iter.hasNext()){
     InD_M3_1_ACTID ind_m3_1 = get_Main().inD_M3_1_ACTID.get(iter.next());
     if(ind_m3_1.WBSLv == 4){
          M3_AF_Activity m3_AF = HM_M3_Act.get(ind_m3_1.WBS);

          // Predecessors
          if(!ind_m3_1.Predecessors.equals("")){
               String[] predArray = ind_m3_1.Predecessors.split(",");

               for(int i=0; i<predArray.length; i++){
                    String[] dpncArray = predArray[i].split("\\[");
                    String WBS       = dpncArray[0];
                    String logic = null;
                    int lagTime      = 0;

                    if(dpncArray.length == 2){
                         dpncArray[1] = dpncArray[1].replace("]","");
                         dpncArray[1] = dpncArray[1].replace("d","");

                         String[] logicLag = dpncArray[1].split("[+]");
                         logic = logicLag[0];
                         if(logicLag.length == 2)
                              lagTime = Integer.parseInt(logicLag[1]);
                    }

                    // Create Dependency

                    Entity_Dependency dpdc = new Entity_Dependency();

                    dpdc.m3_act          = HM_M3_Act.get(WBS);
                    dpdc.dependency = logic;
                    dpdc.lagTime    = lagTime;

                    m3_AF.AL_list_Predecessor.add(dpdc);
               }
          }
          m3_AF.num_Predecessors = m3_AF.AL_list_Predecessor.size();


          // Successors
          if(!ind_m3_1.Successors.equals("")){
               String[] predArray = ind_m3_1.Successors.split(",");

               for(int i=0; i<predArray.length; i++){
                    String[] dpncArray = predArray[i].split("\\[");
                    String WBS       = dpncArray[0];
                    String logic = null;
                    int lagTime      = 0;

                    if(dpncArray.length == 2){
```

```
                                dpncArray[1] = dpncArray[1].replace("]","");
                                dpncArray[1] = dpncArray[1].replace("d","");

                                String[] logicLag = dpncArray[1].split("[+]");
                                logic = logicLag[0];
                                if(logicLag.length == 2)
                                     lagTime = Integer.parseInt(logicLag[1]);
                           }

                           // Create Dependency

                           Entity_Dependency dpdc = new Entity_Dependency();

                           dpdc.m3_act          = HM_M3_Act.get(WBS);
                           dpdc.dependency = logic;
                           dpdc.lagTime    = lagTime;

                           if(dpdc.dependency != null && (dpdc.dependency.equals("SS") ||
dpdc.dependency.equals("SF")))
                                m3_AF.AL_list_SuccessorSS.add(dpdc);
                           else
                                m3_AF.AL_list_SuccessorFS.add(dpdc);
                      }
                }
           }
     }


     // Set Initial Parameters
     iter = HM_M3_Act.keySet().iterator();
     while(iter.hasNext()){
          M3_AF_Activity m3_AF = HM_M3_Act.get(iter.next());

          //Set Module_Activation
          m3_AF.state_dp_MatDelivery = !get_Main().Activate_M1;
          m3_AF.state_dp_SpaceOccupy = !get_Main().Activate_M2;

          //Set Duration
          m3_AF.set_Duration();
     }


}
```

■ Class of Activity Agent <M3_AF_Activity>

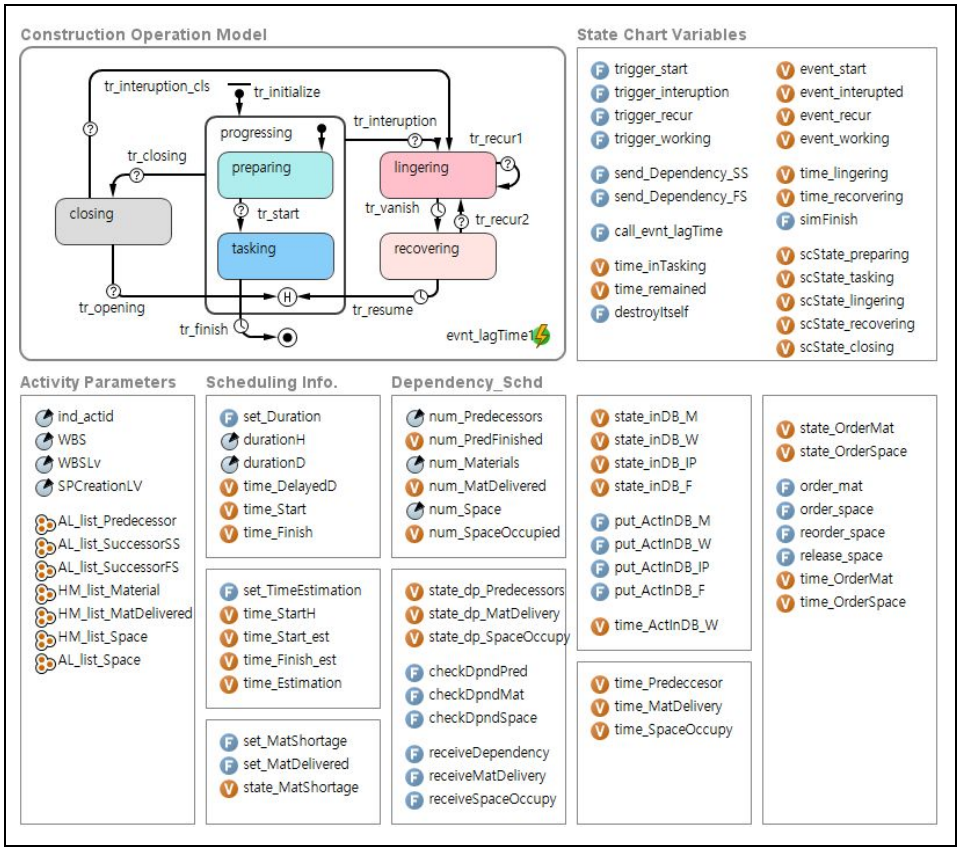

Figure 1-B-10. Picture of <M3_AF_Activity> class in Anylogic 7.1

// Function of [set_Duration]: setting duration of activity based on probability distribution of work productivity

```
Public void set_Duration ()
{
     m3_AF.numExec_set_Duration++;
     M3_AF m3_af = get_Main().m3_AF;

     if(durationH == -1){
          String WBSL3 = get_Main().inD_M3_3_WBS.get(this.WBS).UpperWBS;
          float[] prodArray = get_Main().inD_M3_2_Prod.get(WBSL3).prodArray;
```

```
        double randomNum = uniform();

        boolean checkProd = false;
        Loop:
        for(int i=0; i<prodArray.length-1; i++){
            if(prodArray[i]!=prodArray[i+1]){
                if(prodArray[i]<randomNum && randomNum<prodArray[i+1]){
                    durationH = (i+1)*get_Main().m3_AF.workingHour;
                    time_remained = durationH;
                    checkProd = true;
                    break Loop;
                }
            }
        }

        durationD = (int)durationH/m3_af.workingHour;

        if(!checkProd)
            traceln("FatalError[M3_AF_Activity]: no duration > "+ this.WBS);
    }
}
```

// Function of [set_TimeEstimation]: estimating start and finish time of construction activity agent

```
import java.text.*;
import java.util.Calendar;
import javax.swing.text.MaskFormatter;

Public void set_TimeEstimation(Date referTime, int LV)
{
    m3_AF.numExec_set_TimeEstimation++;

    boolean checkOverrap      = false;
    boolean checkRenew        = true;

    Date dateCrt = date();

    Calendar calRef = Calendar.getInstance();
    calRef.setTime(referTime);

    Calendar calCrt = Calendar.getInstance();
    calCrt.setTime(dateCrt);

    Calendar calStart = Calendar.getInstance();
    Calendar calPreEst = Calendar.getInstance();
    Calendar calFinish = Calendar.getInstance();
```

```
if(time_Estimation != null && time_Estimation.equals(dateCrt)){
     checkOverrap = true;
     calPreEst.setTime(time_Start_est);
}
else
     time_Estimation = dateCrt;

// tStart_estimated

calStart.setTime(referTime);

if(time_Start!=null){
     time_Start_est = time_Start;
     calStart.setTime(time_Start_est);
}
else{
     int referHour = calRef.get(Calendar.HOUR_OF_DAY);

     if(referHour<m3_AF.tWorkingStart){
          calStart.set(Calendar.HOUR_OF_DAY, m3_AF.tWorkingStart);
          time_Start_est = calStart.getTime();
     }
     else if(m3_AF.tWorkingStart <= referHour && referHour < m3_AF.tWorkingFinish){
          time_Start_est = calStart.getTime();
     }
     else if(m3_AF.tWorkingFinish <= referHour){
          calStart.add(Calendar.DATE, 1);
          calStart.set(Calendar.HOUR_OF_DAY, m3_AF.tWorkingStart);
          time_Start_est = calStart.getTime();
     }
     else{
          traceln("FatalError[M3ACT8FH3JD]: Wrong Date Foramt(HH");
          finishSimulation();
     }

     calStart.setTime(time_Start_est);

     if(checkOverrap){
          if(calPreEst.getTimeInMillis() > calStart.getTimeInMillis()){
               calStart = calPreEst;
               checkRenew = false;
          }
     }
}

// tFinish_estimated

calFinish.setTime(time_Start_est);

if(checkRenew){
     if(time_Start!=null){

          int hour   = calFinish.get(Calendar.HOUR_OF_DAY);
          int min    = calFinish.get(Calendar.MINUTE);
```

```
                if(hour==8 && min==00){
                     calFinish.add(Calendar.DATE, durationD +time_DelayedD-1);
                     calFinish.set(Calendar.HOUR_OF_DAY, m3_AF.tWorkingFinish);
                }
                else if ((hour == 8 && min > 0)|| hour > 8){
                     calFinish.add(Calendar.DATE, durationD +time_DelayedD);
                }
                else{
                     traceln("FDG#@FEWFEWFE-1: "+hour+" /"+min);
                }
                time_Finish_est = calFinish.getTime();
           }
           else{
                int hour   = calFinish.get(Calendar.HOUR_OF_DAY);
                int min    = calFinish.get(Calendar.MINUTE);

                if(hour==8 && min==00){
                     calFinish.add(Calendar.DATE, durationD-1);
                     calFinish.set(Calendar.HOUR_OF_DAY, m3_AF.tWorkingFinish);
                }
                else if ((hour == 8 && min > 0)|| hour > 8){
                     calFinish.add(Calendar.DATE, durationD);
                }
                else{
                     traceln("FDG#@FEWFEWFE-2: "+hour+" /"+min);
                }

                time_Finish_est = calFinish.getTime();

           }
      }

      // Save Estimated Data
      if(!state_inDB_M){
           put_ActInDB_M();
      }

      // Successors
      if(!checkOverrap || checkRenew){
           LV++;
           for(Entity_Dependency dpnc:AL_list_SuccessorSS){

                Calendar calNext = Calendar.getInstance();
                calNext.setTime(time_Start_est);
                calNext.add(Calendar.DATE, (int)dpnc.lagTime);

                double timeRangeSF = (calNext.getTimeInMillis()-
calCrt.getTimeInMillis())/3600000d;

                if(timeRangeSF  < m3_AF.maxActivateTime*m3_AF.hourPerDay){

                     if(timeRangeSF > 0 && !dpnc.m3_act.event_start){
                          dpnc.m3_act.set_TimeEstimation(calNext.getTime(),LV);
```

```
                    }
                }
            }

            for(Entity_Dependency dpnc:AL_list_SuccessorFS){

                Calendar calNext = Calendar.getInstance();
                calNext.setTime(time_Finish_est);
                calNext.add(Calendar.DATE, (int)dpnc.lagTime);

                double timeRangeFF = (calNext.getTimeInMillis()-
calCrt.getTimeInMillis())/3600000d;

                if(timeRangeFF < m3_AF.maxActivateTime*m3_AF.hourPerDay){
                    dpnc.m3_act.set_TimeEstimation(calNext.getTime(),LV);
                }
            }
        }
}
```

// Function of [trigger_start]: triggering start event of construction activity

```
Public void trigger_start()
{
    if(!event_start && state_dp_MatDelivery && state_dp_SpaceOccupy &&
state_dp_Predecessors && state_inDB_W){
        // prohibit from begining work at 5:00 pm
        double hour = time()%24;

        if(hour>=17){
            event_working = false;
            create_event_trigger_start(13);
        }
        else{
            event_start = true;
            tr_initialize.onChange();
        }

        set_MatDelivered();
    }}
```

■ Class of Weather Generation Model <M3_AF_Risk1>

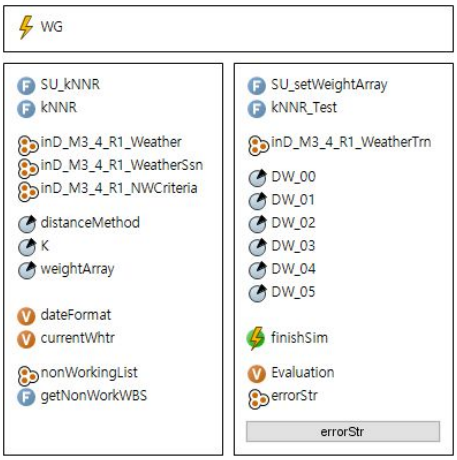

Figure 1-B-11. Picture of <M3_AF_Activity> class in Anylogic 7.1

// Function of [kNNR]: k-nearest neighbor time-series resampling

```
Public void kNNR()
{
     // [b] loading season DB

     int currentSeason = Integer.parseInt(dateFormat.format(date()));
     LinkedHashMap<Integer, InD_M3_4_R1_Weather> seasonDB =
inD_M3_4_R1_WeatherSsn.get(currentSeason);

     // [d] Finding KNNs
     Iterator iter = seasonDB.keySet().iterator();

     ArrayList<Integer> kNNs_Name = new ArrayList<Integer>();
     ArrayList<Double> kNNs_Dist = new ArrayList<Double>();

     while(iter.hasNext()){
          InD_M3_4_R1_Weather knn = seasonDB.get(iter.next());
          float[] kNNVec = knn.dataArray;

          double similarity = 0;
          for(int j=0; j<6; j++)
               similarity += weightArray[j]*Math.pow(currentWhtr[j]-kNNVec[j], 2);
          similarity = Math.sqrt(similarity);
```

```
        // Sorting and Saveing nearest KNN
        if(kNNs_Name.isEmpty()){
            kNNs_Name.add(knn.WDID);
            kNNs_Dist.add(similarity);
        }
        else{
            boolean checkAdd = false;
            LoopKNN:
            for(int j=0; j<kNNs_Dist.size(); j++){
                if(similarity < kNNs_Dist.get(j)){
                    kNNs_Name.add(j, knn.WDID);
                    kNNs_Dist.add(j, similarity);
                    checkAdd = true;
                    break LoopKNN;
                }
            }
            if(!checkAdd){
                kNNs_Name.add(knn.WDID);
                kNNs_Dist.add(similarity);
            }

            if(kNNs_Name.size()>K){
                kNNs_Name.remove(K);
                kNNs_Dist.remove(K);
            }
        }
    }

    // [d] randomSelection of KNN
    int selectedKNN = -1;

    double rnd = uniform();
    double sigmaSim = 0d;
    for(int j=0; j<kNNs_Dist.size(); j++)
        sigmaSim += kNNs_Dist.get(j);

    ArrayList<Double> kNNs_Dist_CDF = new ArrayList<Double>();

    if(sigmaSim>0){
        kNNs_Dist_CDF.add(kNNs_Dist.get(0)/sigmaSim);
        for(int j=1; j<kNNs_Dist.size(); j++){
            kNNs_Dist_CDF.add(kNNs_Dist_CDF.get(j-1)+(kNNs_Dist.get(j)/sigmaSim));
        }
    }
    else{
        double equalRate = 1.0d/kNNs_Dist.size();
        for(int j=0; j<kNNs_Dist.size(); j++)
            kNNs_Dist_CDF.add(equalRate*(j+1));
    }

    LoopSelection:
    for(int j=0; j<kNNs_Dist_CDF.size(); j++){
        if(rnd < kNNs_Dist_CDF.get(j)){
            selectedKNN = j;
```

```
                break LoopSelection;
            }
        }


        int selectedKNNID = 0;
        try{
            selectedKNNID = kNNs_Name.get(selectedKNN);
        }catch(ArrayIndexOutOfBoundsException e){
            for(String str:errorStr)
                traceln(str);
            for(Double dbl:kNNs_Dist)
                traceln(dbl);
        }

        InD_M3_4_R1_Weather SelectedKNN_t1 = inD_M3_4_R1_Weather.get(selectedKNNID);

        currentWhtr = SelectedKNN_t1.dataArray;

        /*
        String str ="";
        for(int i=0; i<currentWhtr.length; i++){
            str += currentWhtr[i]+"\t";
        }
        traceln("## "+str);
        */
        getNonWorkWBS();
}
```

■ Class of Activity Agent <M4_IF>

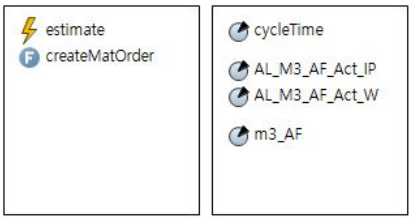

Figure 1-B-12. Picture of <M4_IF> class in Anylogic 7.1

// Function of [createMatOrder]: creating material supply order

```
Public void trigger_start()
{

     // setEstTime
     Date date = date();
     for(M3_AF_Activity m3_act : AL_M3_AF_Act_IP){
          m3_act.set_TimeEstimation(date, 0);
     }

     // putInDB_W
     Calendar calCrt = Calendar.getInstance();
     calCrt.setTime(date());

     ArrayList<M3_AF_Activity> list_act_puinDB_W = new ArrayList<M3_AF_Activity>();

     for(M3_AF_Activity m3_act:m3_AF.AL_M3_Act_M){
          boolean checkAllPred = true;

          LoopPred:
          for(Entity_Dependency dpnc:m3_act.AL_list_Predecessor){
               M3_AF_Activity pred_act   = dpnc.m3_act;
               if(pred_act.time_Finish_est == null){
                    checkAllPred = false;
                    break LoopPred;
               }
          }

          if(checkAllPred){
               Calendar calStart = Calendar.getInstance();
               calStart.setTime(m3_act.time_Start_est);

               double  timeRange = (calStart.getTimeInMillis()-
calCrt.getTimeInMillis())/3600000d;
               if(timeRange <= m3_AF.maxActivateTime*m3_AF.hourPerDay){
                    list_act_puinDB_W.add(m3_act);
               }
          }
     }

     for(M3_AF_Activity m3_act:list_act_puinDB_W)
          m3_act.put_ActInDB_W();
}
```

■ Class of Simulation Results Analysis <Analysis>

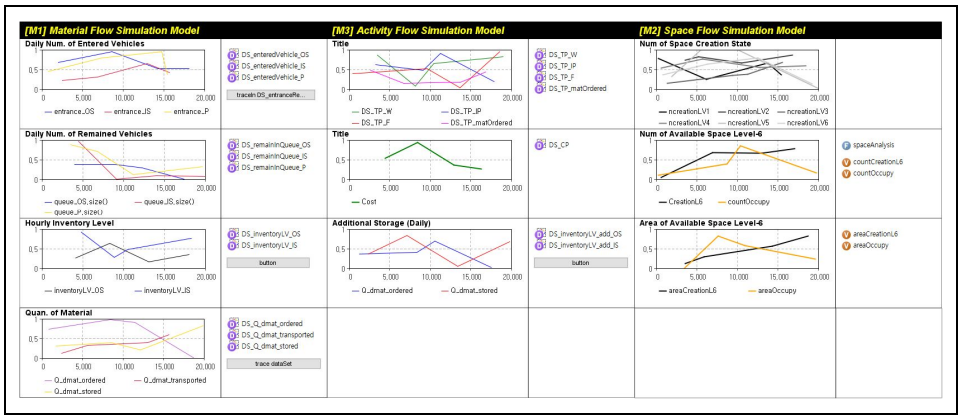

Figure 1-B-13. Picture of <M3_AF_Activity> class in Anylogic 7.1

1-C. Class of CSCM Simulation Entity

■ Class of Entity of Material <Entity_Materials>

```
public class Entity_Material extends Agent implements Serializable {

     //parameter
     public InD_M1_2_MIID ind_miid

     public M1_MF_offSite_WTID m1_wtid
     public M2_SF_Space             m2_space
     public String                  SPID
     public M3_AF_Activity          m3_act

     public int SPCreationLV

     public double Quantity


     // variable
     public boolean expressDelivery = false

     public double leadTime
     public double leadTime_total


    /**
     * Default constructor
     */
    public Entity_Material() {
    }

    /**
     * Constructor initializing the fields
     */
     @Override
     public String toString() {
          return  super.toString()
     }

     /**
      * This number is here for model snapshot storing purpose<br>
      * It needs to be changed when this class gets changed
      */
     private static final long serialVersionUID = 1L

}
```

■ Class of Entity of Material Package <Entity_MatPack>

```
public class Entity_MatPack extends Agent implements Serializable {

     public InD_M1_2_MIID ind_miid

     public double maxQPack
     public double crtQPack

     public ArrayList<Entity_Material> matListInPack = new ArrayList<Entity_Material>()

     public Entity_Inventory inv
     boolean expressDelivery = false

     public double leadTime
     public double leadTime_total


    /**
     * Default constructor
     */
    public Entity_MatPack() {
    }

     @Override
     public String toString() {
          return super.toString()
     }

     /**
      * This number is here for model snapshot storing purpose<br>
      * It needs to be changed when this class gets changed
      */
     private static final long serialVersionUID = 1L

}
```

■ Class of Entity of Transportation Vehicle <Entity_Transport>

```
public class Entity_Transport extends Agent implements Serializable {

     //parameter
     public InD_M1_5_Transportation ind_transp
     public InD_M1_1_WorkType  m1_wtid
     public InD_M1_2_MIID           ind_miid

     public ArrayList<Entity_MatPack> mpackListInTr = new ArrayList<Entity_MatPack>()
```

```
    //variable
    public int TVID

    public double leadTime
    public double leadTime_total

    boolean check_externalStorage = false
    boolean check_expressDelivery = false


    public void set_leadTime_total(){
         for(Entity_MatPack mpack:mpackListInTr){
              mpack.leadTime_total = leadTime_total
              for(Entity_Material dmat:mpack.matListInPack){
                   dmat.leadTime_total = leadTime_total
              }
         }
    }

    public void tracelnLoads(){
         traceln("ind_transp: "+ind_transp.TRType)

         for(Entity_MatPack mpack:mpackListInTr){
              for(Entity_Material dmat:mpack.matListInPack){
                   traceln("\t\t"+dmat.ind_miid.MIID+" "+dmat.m2_space.ind_spid.SPID+"
"+dmat.m3_act.ind_actid.WBS+" "+dmat.Quantity)
              }
         }
    }


   /**
    * Default constructor
    */
   public Entity_Transport() {.
   }

    @Override
    public String toString() {
         return super.toString()
    }

    /**
     * This number is here for model snapshot storing purpose<br>
     * It needs to be changed when this class gets changed
     */
    private static final long serialVersionUID = 1L

}
```

■ Class of Entity of Inventory Cell <Entity_Inventory>

```
public class Entity_Inventory implements Serializable {

     public InD_M1_2_MIID ind_miid
          public String hyphen = "-"

     //public float packSize

     public LinkedHashMap<String, Entity_Material> dmatList = new LinkedHashMap<String,
Entity_Material>()
     public LinkedHashMap<String, Entity_Material> dmatInWaitList = new
LinkedHashMap<String, Entity_Material>()

     public double crtQMat
     public double crtQPack
     public double inventoryLV

     boolean expressDelivery = false

     // analysis

     ArrayList<Double> TS_inventoryX = new ArrayList<Double>()
     ArrayList<Double> TS_inventoryY = new ArrayList<Double>()
     boolean checkDataExist = false


     public void calCrtQmat(){
          crtQMat = 0
          Iterator iter = dmatList.keySet().iterator()
          while(iter.hasNext()){
               Entity_Material dmat = dmatList.get(iter.next())
               crtQMat += dmat.Quantity
          }

          iter = dmatInWaitList.keySet().iterator()
          while(iter.hasNext()){
               Entity_Material dmat = dmatInWaitList.get(iter.next())
               crtQMat += dmat.Quantity
          }
     }

     public void calCrtQPack(){
          crtQPack =
crtQMat/(ind_miid.ItemUnitCalc*ind_miid.PackUnitCalc*ind_miid.InventoryPile)
     }

     public void calInventoryLV(){
          inventoryLV = Math.ceil(crtQPack) * ind_miid.PackArea
     }

     public void addInventory_add(Entity_Material dmat){
          dmatList.put("K"+dmat, dmat)
```

```
            calCrtQmat()
            calCrtQPack()
            calInventoryLV()
      }

      public void removeInventory_add(Entity_Material dmat){
            dmatList.remove("K"+dmat)
            calCrtQmat()
            calCrtQPack()
            calInventoryLV()
      }

      public void addInventory(Entity_Material dmat){

            // Key Setting
            String key = null
            if(dmat.m2_space!=null)   key =
dmat.m3_act.WBS+hyphen+dmat.m2_space.ind_spid.SPID
            else                      key = dmat.m3_act.WBS

            // Function
            if(dmatList.containsKey(key)){
                  Entity_Material dmat_p = dmatList.get(key)
                  dmat_p.Quantity += dmat.Quantity
            }
            else{
                  dmatList.put(key, dmat)
                  Entity_Material dmatInWait = new Entity_Material()
                  dmatInWait.ind_miid  = dmat.ind_miid
                  dmatInWait.m1_wtid        = dmat.m1_wtid
                  dmatInWait.m2_space       = dmat.m2_space
                  dmatInWait.m3_act         = dmat.m3_act
                  dmatInWait.SPCreationLV = dmat.SPCreationLV
                  dmatInWait.expressDelivery = dmat.expressDelivery
                  dmatInWaitList.put(key, dmatInWait)
            }
            crtQMat += dmat.Quantity
            calCrtQPack()
            calInventoryLV()
      }

      public void removeInventory(Entity_Material dmat){

            // Key Setting
            String key = null
            if(dmat.m2_space!=null)   key =
dmat.m3_act.WBS+hyphen+dmat.m2_space.ind_spid.SPID
            else                      key = dmat.m3_act.WBS

            // Function
            if(dmatList.containsKey(key)){
                  dmatList.remove(key)

                  calCrtQmat()
```

```
                calCrtQPack()
                calInventoryLV()
            }
            else{
                traceln("Error[removeInventory] no containsKey (1)")
                traceln("\t"+key)
            }
        }

        public void addHoistedMat(Entity_Material dmat){

            // Key Setting
            String key = null
            if(dmat.m2_space!=null)   key =
dmat.m3_act.WBS+hyphen+dmat.m2_space.ind_spid.SPID
            else                      key = dmat.m3_act.WBS

            // Function
            if(dmatInWaitList.containsKey(key)){
                Entity_Material dmatInWait = dmatInWaitList.get(key)
                dmatInWait.Quantity += dmat.Quantity
            }
            else{
                traceln("Error[addHoistedMat] no containsKey (1)")
                traceln("\t"+key)
            }

            if(dmatList.containsKey(key)){
                Entity_Material dmatInList = dmatList.get(key)
                dmatInList.Quantity -= dmat.Quantity

                if(dmatInList.Quantity < 0.00001)   dmatInList.Quantity = 0
                calCrtQmat()
                calCrtQPack()
                calInventoryLV()
            }
            else{
                traceln("Error[addHoistedMat] no containsKey (2)")
                traceln("\t"+key)
            }
        }

        public void removeHoistedMat(Entity_Material dmat){

            // Key Setting
            String key = null
            if(dmat.m2_space!=null)   key =
dmat.m3_act.WBS+hyphen+dmat.m2_space.ind_spid.SPID
            else                      key = dmat.m3_act.WBS

            // Function
            if(dmatInWaitList.containsKey(key)){
                Entity_Material dmatInWait = dmatInWaitList.get(key)
                dmatInWait.Quantity -= dmat.Quantity
```

```
                if(dmatInWait.Quantity < 0.0001)          dmatInWait.Quantity = 0

                calCrtQmat()
                calCrtQPack()
                calInventoryLV()
            }
            else{
                traceln("Error[removeHoistedMat] no containsKey")
                traceln("\t"+key)
            }
        }

    /**
     * Default constructor
     */
    public Entity_Inventory() {
    }

     @Override
     public String toString() {
          return super.toString()
     }

     /**
      * This number is here for model snapshot storing purpose<br>
      * It needs to be changed when this class gets changed
      */
     private static final long serialVersionUID = 1L

}
```

■ Class of Entity of Schedule Dependency <Entity_Dependency>

```
public class Entity_Dependency implements Serializable {

      M3_AF_Activity m3_act
      String dependency
      float lagTime

    /**
     * Default constructor
     */
    public Entity_Dependency() {
    }
```

```
    @Override
    public String toString() {
        return super.toString()
    }

    /**
     * This number is here for model snapshot storing purpose<br>
     * It needs to be changed when this class gets changed
     */
    private static final long serialVersionUID = 1L
}
```

■ Class of Entity of Delivered Material <Entity_deliveredMat>

```
public class Entity_deliveredMat implements Serializable {

    public Entity_Material dmat
    public double deliveredQuantity
    public boolean state_deliveryComplete = false

    public boolean checkDeliveryComplete(){
        //traceln("dmat.Quantity: "+dmat.Quantity)
        //traceln("deliveredQuantity: "+deliveredQuantity)

        if(dmat.Quantity *0.99 <= deliveredQuantity)
            state_deliveryComplete = true
        else
            state_deliveryComplete = false

        return state_deliveryComplete
    }

   /**
    * Default constructor
    */
   public Entity_deliveredMat(Entity_Material dmat) {
    this.dmat = dmat
   }

    @Override
    public String toString() {
        return super.toString()
    }

    /**
     * This number is here for model snapshot storing purpose<br>
```

```
     * It needs to be changed when this class gets changed
     */
    private static final long serialVersionUID = 1L
}
```

1-D: Database for CSCM Simulation Model

■ Database of Type of Construction Work <InD_M1_1_WorkType>

Data Type	Name	Description
String	WTID	ID code of type of construction work
String	WTName	Name of type of construction work

■ Database of Type of Material Item <InD_M1_2_BQID>

Data Type	Name	Description
String	BQID	ID code of type of material item
String	MIID	ID code of material item in BOQ
double	MIQuan	Quantity of material item
String	SPID	ID code of type of space
String	WTID	ID code of type of construction work
String	WBSL3	ID code of Level-3 WBS
String	WBS	ID code of WBS

■ Database of Material Item in BOQ <InD_M1_2_MIID>

Data Type	Name	Description
String	MIID	ID code of material item in BOQ
String	MIName	Name of material item in BOQ
String	MISpec	Specification of material item in BOQ
String	MIUnit	Quantity unit of material item in BOQ
String	MIQuan	Quantity of material item in BOQ

String	WTID	ID code of type of construction work
int	storageType	Type of on-site yard storage
int	hoistType	Type of hoisting equipment
String	ItemUnit	Unit of material item used in Entity_Materials
float	ItemUnitCalc	Conversion ratio from the quantity of material item in BOQ to that in Entity_Materials
String	PackUnit	Unit of material package used in Entity_MatPack
float	PackUnitCalc	Conversion ratio from the quantity of material item in Entity_Materials to that in Entity_MatPack
float	PackWeight	Weight of the material package for this material item
float	PackLength	Length of the material package for this material item
float	PackWidth	Width of the material package for this material item
float	PackArea	Floor area of the material package for this material item
int	InventoryPile	The number of layer of material packages piled up in storage

■ Database of Site Information <InD_M1_3_SiteInfo>

Data Type	Name	Description
String	SiteID	ID code of construction site
String	SiteName	Name of construction site
float	ExStrgArea	Area of yard storage space outside of buildings
float	InStrgArea	Area of yard storage space inside of buildings

■ Database of Hoisting Equipment <InD_M1_4_HoistEquip>

Data Type	Name	Description
String	TypeCode	ID code of type of hoisting equipment
String	SpecName	Specification of hoisting equipment
int	numEquipment	Number of hoisting equipment

float	Capa_weight	Dead weight capacity of hoisting equipment
int	Capa_matPack	Capacity of material package
float	Speed	Lifting speed
int	ServiceRange_Start	Start floor of range of service floor of hoisting equipment
int	ServiceRange_End	End floor of range of service floor of hoisting equipment
float	delayLoading	Time of loading material packages
float	delayMoveH1	1st Time of moving material packages in a horizontal way
float	delayMoveH2	2nd Time of moving material packages in a horizontal way
float	delayUnloading	Time of unloading material packages

■ Database of Transportation Vehicles <InD_M1_5_Transportation>

Data Type	Name	Description
String	TRType	ID code of type of transportation vehicle
double	TRWeight	Dead weight capacity of cargo space of transportation vehicle
double	TRWidth	Width of cargo space of transportation vehicle
double	TRLength	Length of cargo space of transportation vehicle

■ Database of Building Space <InD_M2_1_SPID>

Data Type	Name	Description
String	SPID	ID code of building space
int	LV	Level of space in space hierarchy structure
String	SPL1Code	ID code of level-1 building space of this space
String	SPL1Name	Name of level-1 building space of this space
String	SPL2Code	ID code of level-2 building space of this space

String	SPL2Name	Name of level-2 building space of this space
String	SPL3Code	ID code of level-3 building space of this space
String	SPL3Name	Name of level-3 building space of this space
String	SPL4Code	ID code of level-4 building space of this space
String	SPL4Name	Name of level-4 building space of this space
String	SPL5Code	ID code of level-5 building space of this space
String	SPL5Name	Name of level-5 building space of this space
String	SPName	ID code of building space
double	SPArea	Name of building space
String	upperSPID	ID code of upper building space in space hierarchy structure

■ Database of Work Breakdown Structure (WBS) <InD_M3_3_WBS>

Data Type	Name	Description
String	WBS	ID code of WBS
String	ActName	Name of WBS
String	UpperWBS	Upper ID code of WBS

■ Database of Construction Activity <InD_M3_1_ACTID>

Data Type	Name	Description
String	ACID	ID code of construction activity
String	WBS	ID code of WBS
int	WBSLv	Level of WBS
String	Name	Name of construction activity
int	Duration	Planned duration of construction activity
Date	Start_Date	Planned start date of construction activity
Date	Finish_Date	Planned finish date of construction activity

String	Predecessors	ACID, dependency, lag time of predecessor activities
String	Successors	ACID, dependency, lag time of successor activities
String	SPLIST	ID code of building space
int	SPCreationLV	Space creation level after this construction activity

■ Database of Work Productivity <InD_M3_2_Prod>

Data Type	Name	Description
String	WBS	ID code of WBS
float[]	prodArray	Data array of productivity

■ Database of Threshold Criteria of Non-Working Day due to Severe Weather <InD_M3_4_R1_NWCriteria>

Data Type	Name	Description
String	typeACT	Activity
String	WBSL3	ID code of level-3 WBS
float	TMX	Threshold value of maximum temperature
float	TMN	Threshold value of minimum temperature
float	WSPD	Threshold value of wind speed
float	P	Threshold value of precipitation

■ Database of Historical Weather <InD_M3_4_R1_Weather>

Data Type	Name	Description
int	WDID	ID code of historical weather data
int	Year	Year of data

int	Month	Month of data
int	Day	Day of data
int	JD	Julian day of data
float[6]	dataArray	Data array of value of weather factors: solar radiation; daily maximum temperature; daily minimum temperature; wind speed; temperature of dew point; precipitation

국 문 초 록

건설 공급사슬관리의 복잡성: 초고층빌딩 프로젝트의 행위자기반 시뮬레이션

기존의 건설관리 기법 및 관련연구는, 건설생산시스템의 구성요소 및 하위시스템들이 상호독립적이고, 각 구성요소에 대한 입출력 요소의 관계가 선형적이라는 환원주의적 관점에 기초하여 왔다. 그리하여, 전체시스템을 계층적으로 분류하고, 하위단계의 구성요소가 갖는 개별적인 특성을 밝혀내는 연구가 주로 수행되어 왔다. 하지만 건설생산시스템은 상호의존적인 구성요소와 이루어져 있으며, 구성요소의 개별적인 특성으로는 설명할 수 없는 복잡한 현상이 발생하는 시스템이기 때문에, 환원주의적 관점의 선행연구는 전체 건설생산시스템을 이해함에 있어 한계가 있다. 반면에, 건설 공급사슬관리는 이러한 한계를 극복하기 위하여 전체주의적 관점에 기반하여, 건설생산시스템의 가치생산 작업과 비가치생산작업을 하나의 프로세스로 바라보고, 프로세스 간의, 혹은 하위구성요소 간의 상호관련성을 고려하여 작업흐름을 동기화하고 전체사업의 성과를 향상시키는 것에 의의가 있다.

전세계적으로 급증하고 있는 초고층빌딩 건설사업은, 수 많은 조직, 작업, 자재, 공간, 그리고 정보 등의 구성요소로 이루어진 대규모 프로젝트이고, 공기단축을 위해서 다양한 종류의 작업이 동시에 수행되는 동시시공공법이 주로 적용되고 있는 반면에, 야적공간 및 양중장비와 같이 자재공급을 위한 자원이 상대적으로 제약적인 특징을 갖는다. 이러한 이유로, 초고층빌딩 건설사업의 공급사슬은, 이것을 구성하는 시공 및 자재공급 프로세스 사이에 다양한 상호작용이 발생시킴으로써, 전체

건설생산시스템의 행태를 복잡하게 전개 시킬 수 있다. 하지만 앞서 언급한 바와 같이, 많은 선행연구가 환원주의적 관점에서 수행되어 왔으며, 전체주의적 관점에서 수행된 연구들도 구성요소간의 상호관련성, 그리고 그것이 전체 시스템에 미치는 영향에 대해서 정량적으로 연구하기 보다는, 이론적인 체계를 구축하는 것에 초점을 맞추어 온 것에 한계가 있다.

이에 본 연구는, 초고층빌딩 건설사업의 공급사슬의 구성요소 간에 발생하는 복잡성을 파악하고, 이러한 특성이 전체 건설사업에 미치는 영향을 분석하는 것을 목적으로 한다. 연구의 목적을 달성하기 위해서, (1) 건설공급사슬관리의 연구모델을 제시하고, 이를 토대로 발생 가능한 복잡성에 관한 5가지 가설을 설정하였으며, (2) 가설검증을 위하여 행위자기반 및 이산사건 시뮬레이션 기법을 이용한 정량적 모델을 개발하였으며, 마지막으로 (3) 실제 초고층 빌딩공사 데이터를 적용한 시뮬레이션 실험을 통하여 제시된 가설에 대한 검증을 수행하였다.

본 연구를 통해서 밝혀진 사실은 다음과 같다. (1) 시공 프로세스의 네트워크는, 이질적인 특성을 갖고 지역적으로 연결된 구성요소로 이루어져 있기 때문에, 악천후와 같이 외부 리스크요인이 발생시키는 지역적인 영향과 전체 건설생산시스템의 관계는 선형적이지 않다. (2) 다수의 자재공급 프로세스에 의해 자원이 공유되는 경우, 개별 프로세스의 재고수준을 최적화 하는 Just-In-Time방식에서도, 프로세스간의 간섭현상이 발생할 수 있으며, 이것은 전체 건설생산시스템에 부정적인 영향을 미친다. (3) 작업공간과 내부야적공간 사이에서 발생하는 공간적인 충돌은, 시공 및 자재공급프로세스 사이에서 되먹임 되어, 전체 건설생산시스템에 부정적이고 비선형적인 영향을 미칠 수 있다. (4) 상기의 복잡성을 갖는 건설사업에서, 최소 재고수준을 갖는 Just-In-Time방식은 복잡성으로 인한 부정적인 영향을 상쇄하지 못해 낮은 사업성과를 보이지만, 과도한 재고수준 또한 복잡성을 증대시켜 사업성과를 감소시키기 때문에, 재고수준과 사업성과 사이에 비선형적인

관계가 성립한다. (5) 시공 및 자재공급에 관한 외부 리스크 요인이 건설사업 구성요소의 행위 및 관계를 변화시킴으로써, 재고수준과 사업성과 간의 관계는 고정적이지 않으며 동적으로 변화할 수 있다.

본 연구는, 빌딩건설사업의 공급사슬이 복잡계 시스템의 하나로써, 구성요소 사이의 발생하는 상호의존적인 관계가 전체 생산시스템에 미치는 영향은 각 구성요소의 특성으로 설명할 수 없는 창발적인 특성을 갖는다는 것을 정량적 모델을 통해 밝혀 낸 것에 의의가 있다.

주요어: 건설관리; 공급사슬관리; 생산시스템관리; 복잡계 시스템;
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