Doctor of Philosophy

Planning and Control of Modular Building Construction Projects Using Discrete-Event Simulation

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Abstract

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The modular building construction project demands has been increasing in the construction industry. However, the results of recent research show that the benefits of the schedules of modular building construction are not as per our expectation. One of the reasons is that the scheduling of conventional construction is applied instead of project planning and control which reflects the characteristics of the modular

building construction project constraints and market change flows of modular building construction. Moreover, apart from large construction markets and project sizes companies are faced with a new challenge in their project planning and execution process because of the change from Finish-to-Start work precedence to concurrent work. The concurrent work in modular construction defines that the manufacturing production for constructing a main structure and foundation work for installing a manufactured structure have same Start- To- Finish dates. However, in large-scale projects and increasing modular building construction markets, the previous concurrent work definition is changing as the manufacturing and on-site installation durations are overlapped. This is because of the fact that the previous Finish-To-Start work precedence is not enough to finish the project until the end of the project dates and total number of modular units exceeds the factory storage yard capacity. To address these problems, this research suggested and developed a simulation model for optimizing project resources and schedule of volumetric modular building construction. This simulation model aims at improving a project manager’s understanding of the overall modular building construction project process and providing a reliable resource allocation methods. As a technical approach, this research used a discrete event simulation method to implement the repetitive working on the modular building construction project to enable project schedules from the modular project manager’s

perspective. From an academic point of view, this research showed that the scheduling of the modular construction method requires to be concurrent rather than conventional.

Keywords: Construction Management, Project Planning and Control, Modular Building Construction, Scheduling, Resource Optimization, Discrete Event Simulation

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Chapter 1. Introduction

1.1 Research Background and Motivation

A construction project involves the application of multiple resources to achieve a finished structure (Halpin, 1992). The purpose of project operations of a building construction is to establish a reliable stream of construction processes based on limited initial project information and execute a work activity of the planned process based on collection of actual work information.

Project time and resource management are regarded as key components for a successful project execution. However, when executing a construction project, changes in time and resource availability occur commonly because of low productivity, bad weather, raw material delivery delay, and unpredicted accidents. Hence, a project often requires to update or reschedule considering not over the project due date (Tang, 2014). Before the project planning, PMBOK (fourth edition) emphasized upon a what-if scenario analysis to assess the project planning feasibility under adverse conditions and to prepare contingency response plans to overcome or mitigate the impact of unexpected situations and change of project conditions. In other words, creating a plan that considers time and resources simultaneously is important in the development stage of project optimization.

Currently, the modular construction market is driven by the growth in the construction industry. Furthermore, because of the problems such as lack of skilled labor and low productivity, the construction market demands environment friendly construction and reduction in cost-time trade-off effects. With growing industrialization, the need for time saving construction methods has increased, which has widened the scope of modular construction. The modular construction is a type of manufacturing process, in which 60%-90% of the construction work is performed at a factory and delivered to an installation site (MBI, 2015). One of the most advantages of modular building construction is that it is possible to execute concurrent construction work with the structure and foundation works.

However, the results of recent research show that the schedule benefits of modular building construction are not as per our expectation. The IPA announced that the schedule effectiveness of non-modular, low-modular, and high-modular construction projects is not remarkably different. This result was deduced from 800 projects that used modular construction before the 2014. Next, the result information was converted to non-modular construction and low-modular construction projects. This result shows that the schedule effectiveness exists in modular construction, but is not applicable to all modular building construction projects(Figure 1-1).

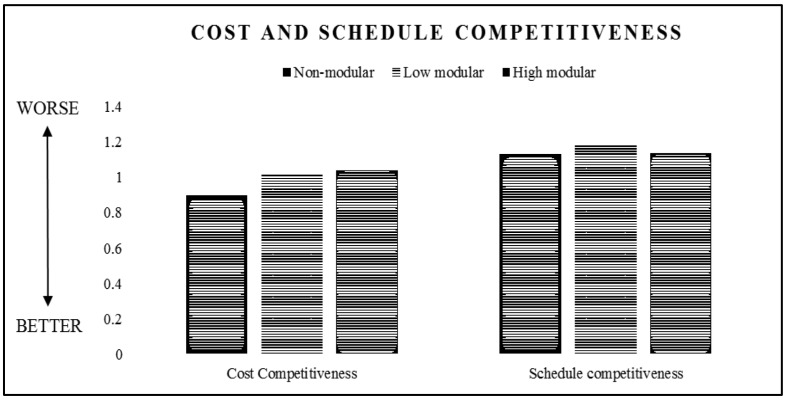


Figure 1-1. Cost and Schedule Competitiveness Between Modular and Non-Modular (resource from Independent Project Analysis (IPA) Newsletter, 2015)

One of the reasons is that the scheduling of conventional construction is applied instead of project operations, which reflects the characteristics of the market change flow of modular building construction. For example, before the construction market and project size are not as much as larger than the current situation, people recognized that the project schedule of modular building construction is shorter than conventional construction because of concurrent schedule execution. Because the total manufacturing production duration was sufficient to manage the total project duration, its duration was the same as the on-site foundation duration and enough to stock the manufactured units in the factory storage yard until the end of foundation work. In short, it means that the finishing dates of the manufacturing production and starting dates of the on-site installation durations fit mostly in the planning and execution of the conventional construction, which has Finish-to-Start work precedence.

Further, with the construction market and project sizes becoming larger than before, companies are faced with a new challenge in their project planning and execution process because of work precedence changing from Finish-to-Start work precedence to concurrent work. The concurrent work in modular construction defines that manufacturing production for constructing a main structure and foundation work for installing a manufactured structure must have the same Start- To- Finish dates. Considering the large scale of the projects and increasing modular building construction market, the previous definition of concurrent work is changing as the manufacturing and on-site installation durations have overlapped. This is because the previous Finish-To-Start work precedence is not enough to finish the project until the due dates and the total number of modular units exceed the factory storage yard capacity.

To complete these types of projects, the manager of the modular building construction, who is charged for managing the manufacturing production and on-site installation, requires manufacturing production schedule (off-site) and site work schedules (on-site). These two schedules have their own Start-to-Finish dates (duration) and work relationships (work precedence) following manufacturing production capacity and daily on-site workability. Thus, these modular building construction projects need reliable alternate construction operations because of the interrelationship between manufacturing, transportation, and installation of finishing before the project due dates.

1.2 Problem Statement

To deal with problems, several researchers have suggested solutions for managing a current modular building construction project.

Lu (2009) investigates the several reasons behind problems related to schedule planning and execution of modular building construction. One of the reasons is that contractors apply for modular building construction that is highly focused on reducing the construction duration and overall project schedule. Moreover, the main challenges in project planning and execution are inherent because of a lack of understanding of the modular building construction process. The research results of Thomas and Sanfido(2000) show that late and out-of-sequence deliveries, fabrication errors, and impartible production rates of on-site installation give rise to problems with modular building construction. Matt(2014) emphasized that the manufacturing production schedule of the conventional modular building construction process has been disconnected from the installation on-site. Thus, it is a barrier to build an optimal project planning and control process. Li (2013) performed risk identification and assessment of modular building construction research based on the Fuzzy and AHP methods. The results show that the high risk factors weights in duration are 1) political and social condition, 2) construction planning, and 3) construction coordination and control. Except the political and social conditions, these factors encompass important schedule integration from manufacturing to on-site installation.

Although results from previous research results are helpful in optimizing the production schedule of a modular building construction project, there exist the following limitations in developing the construction operations of the entire modular building construction project from manufacturing to on-site installation.

From the process perspective, modular construction requires project management strategies that follow the supply chain perspective because modular manufacture is responsible for delivery and assembly of the modules(Velamati, 2012). Accordingly, in modular building construction, it is the project manager who has to decide the durations of manufacturing, transportation, and on-site installation durations considering interrelationships between the work characteristics of each pahase. In other words, the off-site (manufacturing) construction and on-site (installation) construction schedules have to integrate for establishing a reliable schedule (Arashpour, 2016).

However, current modular construction operations are still an application of conventional construction schedule strategies and project planning; focusing on the activity precedence definition, calculating project duration by forward scheduling, and relying on previous project schedule results(Moghadam, 2014). More specifically, the current modular building construction project operations have following limitations and problems.

1) Focusing on Manufacturing scheduling for production optimization

Most of construction work activities are performed at the factory. Accordingly, manufacturing duration is the longest in the modular construction schedule. As a result, its planning preferentially targeted at production optimization for minimizing a production variability and maximizing a daily production unit.

Accordingly, the project manager of modular building construction has less considered to make modular construction schedule considering on-site work. This is because the scale of the previous modular construction projects was not much larger than current manufacturing production capability. Hence, on-site work variability does not play a significant role in manufacturing schedule changes. As a result, the project manager does not perform the entire schedule optimization based on the basic information about the project, but rather performs the specific stage schedule optimization. This result is not a reflection of the various limitations and problems that arise in the project progress. Hence, there is a high possibility of a change in schedule results.

2) Lack of understanding of modular building construction process relationships

Following the classification of construction methods by the conventional construction industry, modular construction is an off-site construction method. In off-site construction, the work related to the main structure (or partial elements) is performed in another place (factory), then delivered and installed at the construction site (on-site).

The main purpose of modular construction planning is that the main structure (or partial elements) are delivered on-time while performing other on-site construction work activities. Hence, the construction industry considered that modular construction scheduling has not different from one of the conventional scheduling purpose of creating and controlling the work activity precedence by CPM/PERT methods. These methods had been assumed for creating and controlling of work activity duration calculation, which is each activity duration, cannot affect other activity duration calculation except Start-Finish dates determined by forward scheduling. It means that the precedence activity duration does not affect next activity duration calculation. When on-site work and manufacturing production schedule changes, however, it is difficult to find which activities least effect to in total construction process because CPM/PERT methods are complicate to express repetitive work schedule. In this regard, the project manager had difficulty controlling the impact of constraints changes on overall project schedule delays. Therefore, if the project constraints were changed, it is difficult to derive the optimum result, which may cause the project schedule delay problem.

1.3 Research Objective and Scope

The main objective of this dissertation is improving modular building project for providing various scheduling options to the project manager through the integration of on/off site construction processes.

To achieve this objective, three specific goals were performed as follows.

1) Investigations of the modular building construction planning principles and requirements based on literature review: in order to define the simulation model requirements and its development way sets, it is necessary to investigate the current problems in making a modular building construction project schedule and to suggest the resource and working time optimization model using limited project information.

2) Development of the optimization model for modular building construction process to analyze the on/off site schedule integration effects and resource utilization using Discrete-Event Simulation: based on the current problems in modular building construction scheduling methods, quantitative models that have availability for application the modular

building construction operations

3) Analysis of scheduling and planning problems in the modular building construction project through the simulation results: using the input data from basic modular building construction project information, sensitivity analysis simulations are carried out to how project manager used this result.

Hence, this research scope is mainly focused on from manufacturing to on-site installation process, except the finishing work at on-site. The type of modular unit is volumetric and production type is a continuous manufacturing process.

1.4 Organization of Dissertation

This dissertation is comprised of five chapters and the details of each chapter are as follows (Figure 1-2).

In chapter 1, briefly reviews the literature and current research of the project planning and scheduling problems in modular building construction.

In chapter 2, identifies the definition of volumetric modular building construction and the characteristics of its production process, transportation, and on-site installation. Next, the investigation of current scheduling and operations problems in modular building construction project and recent research for improving the modular building construction scheduling capability based on Supply Chain Management and Lean construction principles. Following these results, this research defined the four main parts of the schedule optimizing simulation module for modular building construction process application.

In chapter 3, performs the development of simulation models for optimization of modular building construction project's time and resources. This simulation model mainly consists of four parts; pre-work for production, production, transportation, and on-site installation. After the simulation model development, verification of each simulation model is performed based on actual volumetric modular building construction project information.

In chapter 4, performs integration of four different simulation modules into one and the verification of this integrated simulation model is performed based on actual modular building construction project data. Next, this simulation model is applied to actual modular building construction scheduling problems and simulation experiments are carried out. Based on these results, this research presents how the project manager can use the simulation results in scheduling and how the manager can interpret the results.

Finally, in chapter 5, the research results and contribution of this study from the technical point of view and academically point of view are described. Then, this research finally states its limitations and required future work for applying the research results to the real modular building construction project in the future.

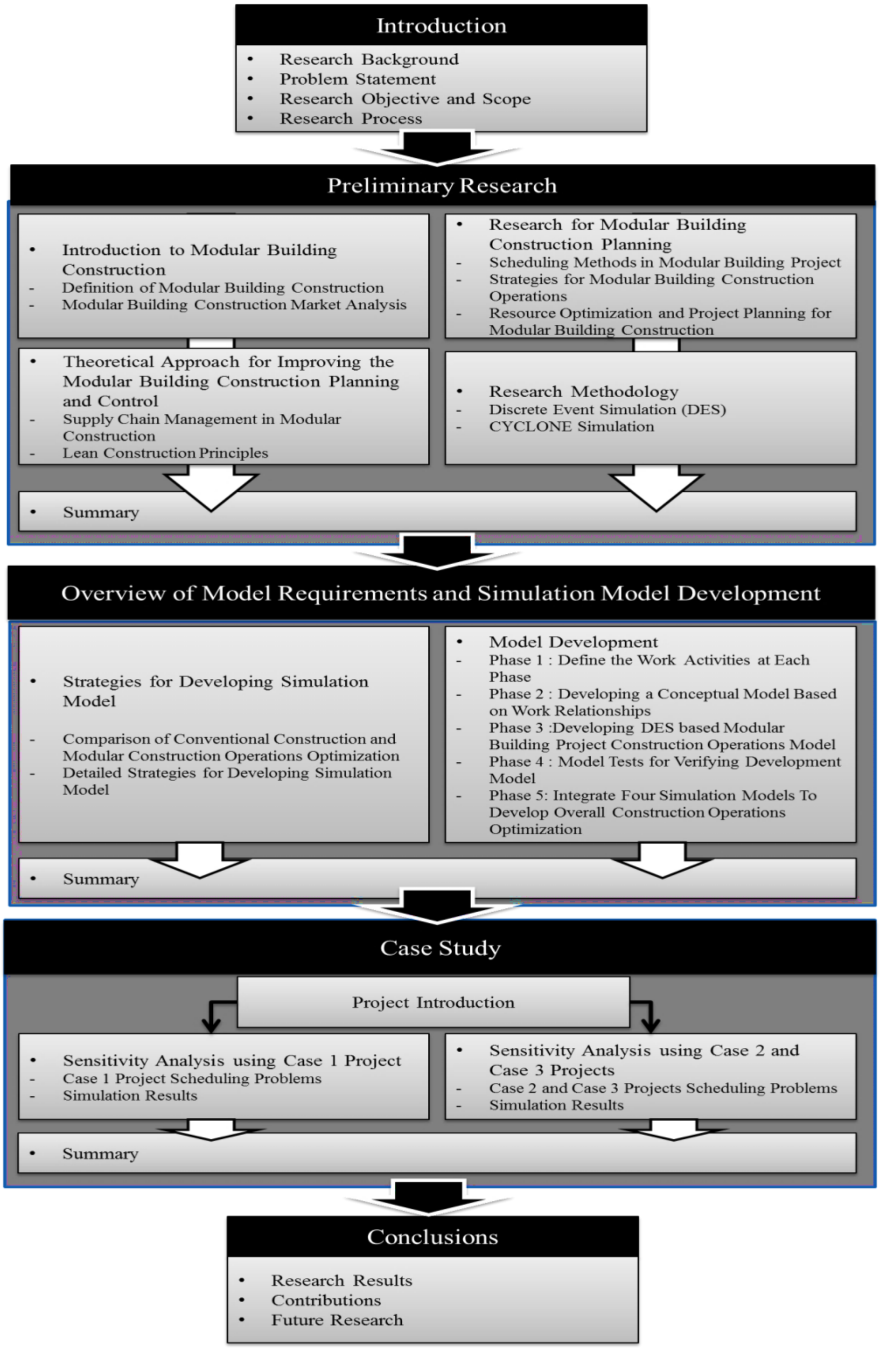


Figure 1-2. Overview of Research Process

Chapter 2. Preliminary Research

This chapter identifies the definition of volumetric modular building construction and characteristics of the production process, transportation, and on-site installation. Following these results, this research defined the four main parts of the simulation model for modular building construction process application.

2.1 Introduction to Modular Building Construction

2.1.1 Definition of Modular Building Construction

Over the last 20 years, off-site construction has been established itselft in the conventional construction industry (Lawson,2014) and there are mainly five categories of off-Site construction definition (Table 2-1 and Figure 2-1). Following the definition of off-site construction categories, the modular construction usually uses three-dimensional or volumetric units which are fully completed in the factory, and are installed on-site to complete building (Figure 2-2).

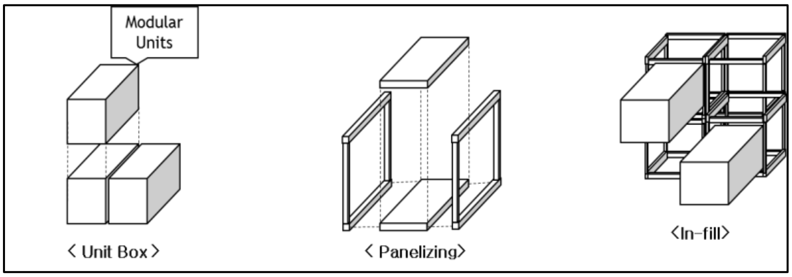


Figure 2-1. Types of Modular Building Construction Structure

In general, “Modular Construction” represents a pre-constructed structure, which is one of the components of the main structure that is built various out of real construction site areas, such as factories, and transported to the site, and to finish the complete structure. For example, in plant construction, a typical pipe-rack and a generating module are moved to the construction site and installed at its position. These modules are not manufactured in one factory because each module has a special performance. Accordingly, its scheduling and control purposes were focused in meeting the delivery deadline of the module while considering yard constraints (Taghaddos,2012). On the other hands, “Modular Building Construction” represents a pre-constructed structure, which is fully completed. The modules are constructed at one factory and delivered on time. According to this, its scheduling and control purposes were focused on synchronizing the manufacturing production schedule and on-site installation schedule for preventing and avoiding the schedule delay.

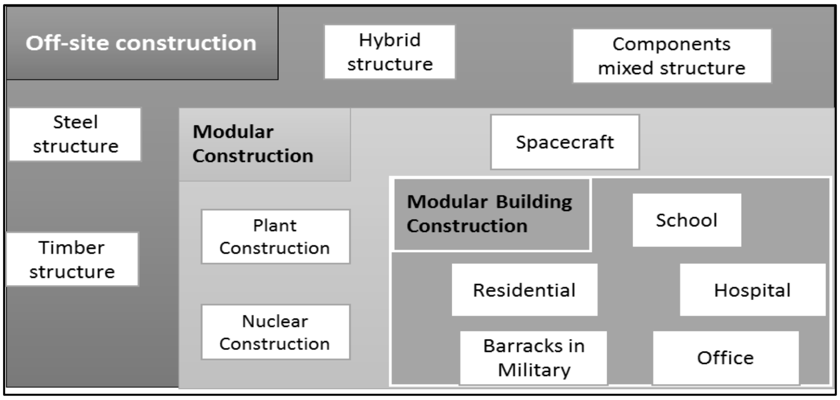


Figure 2-2. Classification of Off-site construction, Modular construction, And Modular building construction

To complete the construction, modular building construction has three main manufacturing processes; static production, cell production, and continuous production. In static production, the modular unit stands in one position in a factory, and materials, services, and workers are brought to the module (Design in Modular Construction, 2014). Its construction rates are decided by the availability of worker for the work activities at the needed time (Figure 2-3). Accordingly, the critical path in each modular unit is not a specific several work activities' sum of duration, but all work activity's duration. For smooth production, it needs sufficient space for temporary storage of materials and pre-finished componentents (Design in Modular Construction, 2014)

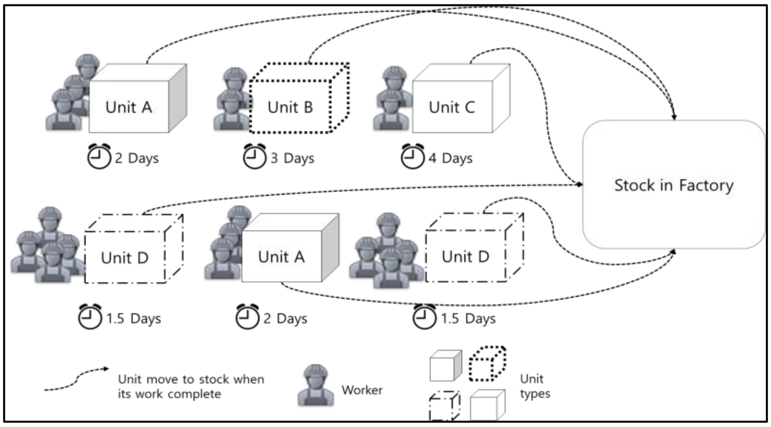


Figure 2-3. Example of Static Production

Cellular manufacturing production has been widely used in modular building construction (Figure 2-4). In cellular manufacturing production, production work stations and equipment are set in line production that provides a smooth flow for the production process and minimizes the transportation time and bottleneck effect. With modular construction, the cellular manufacturing process aims to move a single modular unit through the manufacturing process as per the customer’s needs. In order to achieve this production process, it needs for multi-skilled workers need to perform a variety of tasks and advanced machines for improving workability are required. Thus, this production method is mainly used to carry out specific projects performed by a company having the over certain level of experience in modular project execution.

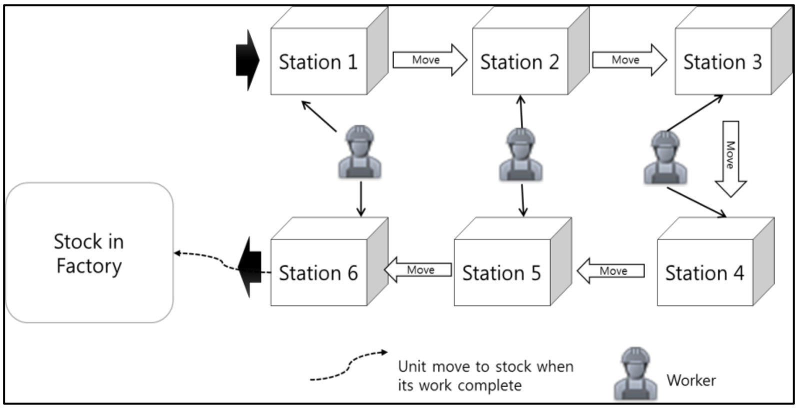


Figure 2-4. Example of Cellular Production

In continuous (linear) production, a modular unit stands on the moveable structure (or jig) and is mobile between stations (Figure 2-5). In this case, workers are not moving and working their work activity at the each work station. Each station has predetermined work activity and workers for completing a modular unit. Its production rates are decided by the work time in each workstation and the number of work stations. Accordingly, critical path in each modular unit is defined by the longest work time activity in each station. In smoothen production, it needs well defined work activity allocation in each work station and work time operations for preventing a bottleneck effect (Goldratt 1992; . Riley and Sanvido 1995; Nahmens, 2012).

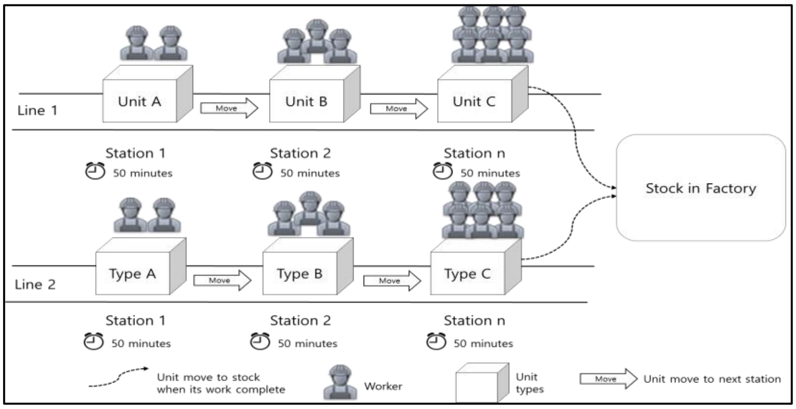


Figure 2-5. Example of Continuous Production

In general, continuous production process is used more than static and cell production processes in modular building construction to achieve reduction in the project duration and construction cost. For example, static production process adapted company cannot deal with mass production needed project because it is difficult to balance production quantity and process performance with each work activity. Thus, this production is difficult to make a schedule because the daily production quantity calculation result is not accurate in necessary projects of a large number of modular units. So, continuous production process has been widely adapted in the modular building construction project.

In the continuous production process, however, there are several issues in the planning of the project. First, it is difficult to deal with a design change. For example, the static production process is easier than a continuous process for dealing with design changes when production is already performing because it does not have to be changing the whole production process. However, continuous process can be carried out just-in-time production and delivery to the installation time because it does not have to be considered each modular unit work team’s productivity.

Second, this process is required to keep the work speed up during the project execution. It is important to keep the daily manufacturing production quantity and daily on-site installation quantity for not only to achieve the uniform quality, but also to improve the productivity (Mehrotra,2003;Duffner,2008; Mohsen,2008). In general, the modular building construction project’s most of the construction work are performed in factories (indoor). Thus, weather effects (rain, high and low temperature, and wind) are less than conventional construction. According to this, it is recognized that modular building construction schedule is more reliable than conventional construction. Considering the manufacturing environment (line production process, different daily productivity because of not fully made by machines) and on-site installation environment (different daily productivity because of unexpected weather change and machine error), however, its schedule has possibility of changes. Thus, the manager has to decide an optimal working speed of manufacturing and installation considering factory workability and on-site workability at the planning for scheduling stage. In addition, project manager always adding an extra time (buffer time) into the working schedule for preparing the schedule delay impact. To deal with these problems in continuous production process, one of the reliable solution is that use the stock in the factory. The modular unit stock in factory is not only effective to deal with over ruing schedules in both manufacturing and on-site installation but also to control the overall transportation schedule. According to this, pre-production products, modular units, stock in factory strategies are helpful to project manager for reducing the impact of changing schedule problem (Figure 2-6).

Table 2-1. Definition of Off-Site construction

Systems	Related References	
	Gibb and Pendlebury, 2006	MMC, 2008
Modular Construction	Three-dimensional or volumetric units that are generally fitted out in a factory and are delivered to the site as the main structural elements of the building	Three-dimensional units produced in a factory, fully fitted out before being transported to site and stacked onto prepared foundations to form dwellings.
Partial Modular Construction	Tow-dimensional panels, used mainly for walls, that can be refinished with their insulation and boarding attached before delivery to site	-
Panelized	-	Flat panel units built in a factory and transported to site for assembly into a three-dimensional structure or to fit within an existing structure
Hybrid Construction	Mixed use of linear elements, panels, and modules to create a mixed-construction system	Volumetric units integrated with panelized systems

Table 2-1. Definition of Off-Site construction(Continue)

Systems	Related References	
	Gibb and Pendlebury, 2006	MMC, 2008
Cladding Panels	Prefabricated façade elements that are attached to the building to form the completed building envelope.	-
Pods	Nonstructural modular units, such as toilets and bathrooms, that are supported directly on the floors of the building	-
Sub-Assemblies and Components	-	Larger components that can be incorporated into either conventionally built or MMC dwellings
Non-Off-Site manufactured MMC	-	Innovative methods of construction used on-site and the use of conventional components in an innovative way

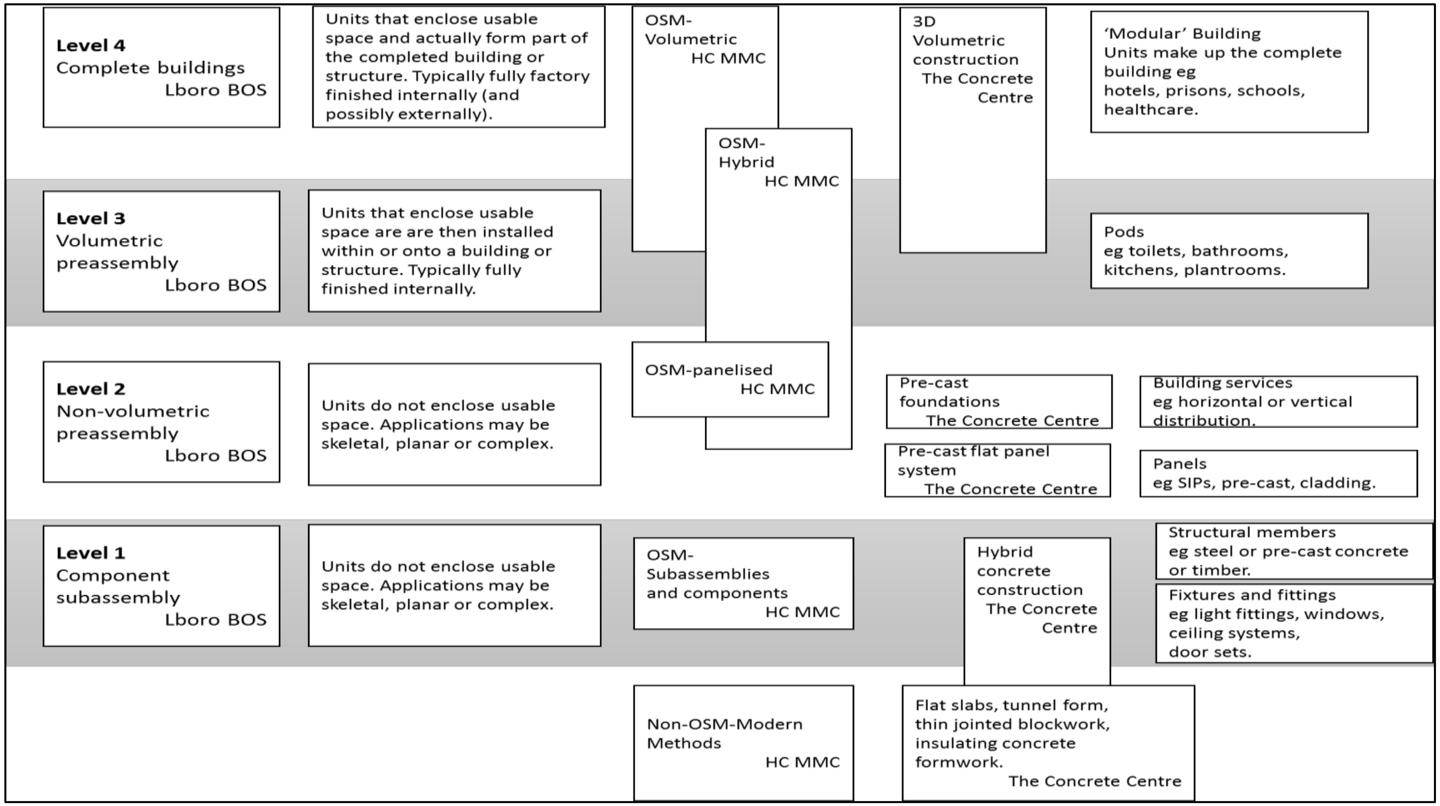


Figure 2-6. Classification of Off-site Construction (Adapted from Gibb, A., & Pendlebury, M. (2006)),

2.1.2 Modular Building Construction Market Analysis

Modular building construction has been increasing interest in adopting and utilizing off-site production technologies in house building in many countries and regions (Wei Pan, 2012; Alazzaz, 2014). For example, permanent modular construction market in North America is about $2 billion and expected additional $4 billion in revenue is generated in the modular construction industry outside of North America (MBI Report, 2011). Recently, the Modular Building Institute(MBI,2015) investigated that modular building construction market will be growing in traditionally string modular markets such as office and educational facilities. In addition, following AMA Research Report (Figure9) Prefabricated Volumetric Building Systems Market Report UK 2016-2020, it emphasized that the demand for the volumetric modular construction project is steadily increasing, and the project size is also increasing (Figure 2-7).

In 2004, the U.S Army began to construct temporary barracks and supporting facilities to accommodate troop units moving onto installations through Army Transformation, re-stationing from locations outside the continental U.S, and other directives (U.S army report, 2003). In the United Kingdom, modular construction has been since the late 1970s, but its rapid increase in recent years has occurred due to client demands in various well-defined sectors (The Steel Construction Institute, 2000). The permanent modular construction market is estimated \$2.44 billion, of which 33% is associated with leasing activity while 67% (\$1.63 billion) is for sales of modular buildings and relocatable modular construction market is estimated between \$5.5 and \$6.0 billion (MBI Report, 2012). In Korea, Ministry of National Defense is pushing ahead with a relocatable military facility to barracks and B.O.Q 140 billion won (2011), 500 billion won(2015). Moreover, various countries and regions such as Japan, Germany, Malyasia, Austria, and Hong Kong have implemented manufactured buildings in the last decade (Pan et al, 2012).

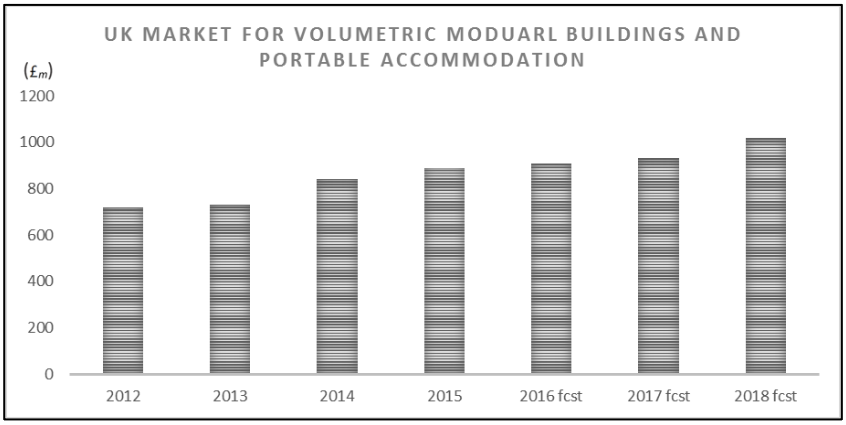


Figure 2-7. Market Increasing in U.K Volumetric Modular Buildings

The Construction Industry Council report (2013) indicates that the scale of modular building construction is getting larger than before and there is an increasing demand by customers for using modular building construction method. The Mcgraw Hill Construction report(2011) performed research for modular building construction market analysis and suggesting a way of increasing productivity in the construction industry. Following this research results, modular construction has been used on many types of building projects such as healthcare, higher education, manufacturing, low rise office, and public.

It emphasizes that modular building construction is not a steady increase in use constantly before the war and economic booms. In the last twenty years, however, advanced technology application in modular building construction leading an increase the market size such as BIM and Lean construction principles. In VANGURAD modular building system release the five trends in modular building construction (www.vanguardmodular.com). Following the article, one of the remarkable change of the modular building construction market is that customer’s perception of modular construction is changing from only one of the option for short-term space needs to one of the alternatives to conventional construction methods. This changes leads the modular building construction market trend changes from single small scale construction project to large scale construction project (Alazzaz, 2014).

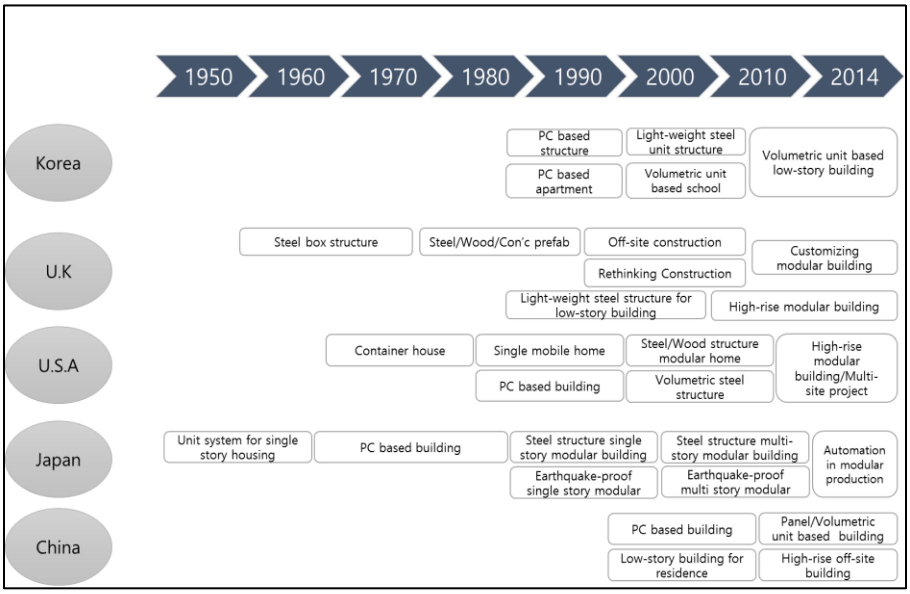


Figure 2-8. Summary of Modular Building Construction Market Changes History

The Modular Building Institute(MBI) has been performing an industry survey every year to provide current modular building construction trends for customer, manufacture, and other contractors (Figue 2-8). From the results of MBI report, U.S and Canada, there are seven general trends indicated; 1) forecasted manufacturer revenue continues to increase, although at less accelerated pace, 2) manufacturers' responses indicated a steady increase in production compared to the previous year, 3) thirty-five percent of manufacturers reported lead times of four weeks or less in the latest quarterly survey, 4) raw materials inflation was essentially flat for the year, 5)approximately thirty seven percent (37%) of all floors produced are for permanent modular buildings, 6)for dealers, leasing revenue growth continues to be a strong point for the industry, with double digit growth rates reported in each quarter, 7) dealers remain optimistic about leasing revenue growth, suggesting a ten percent increase for the year.

SADI(2014) emphasized that modular building construction market is sizable in the construction industry and its stakeholders, customers, and vendors getting increases (Figure 2-9). Nevertheless, lack of understanding of current modular building construction market analysis is one of the barriers for predicting its trends. This research, performed analysis of modular building market based on Modular Building Institute reports data (2013) of modular building construction project from 1994 to 2011. It shows the meaningful results that large amount of modular unit orders constantly increasing and supply dynamics exists between manufacturers and dealers. This research results represent that modular building project manager, who has charged with manufacturing to on site installation, has to prepare for manufacturing strategies considering not only directly contract to a customer, like as conventional construction contract ways, but also project of including dealers who is directly connected with the customer.

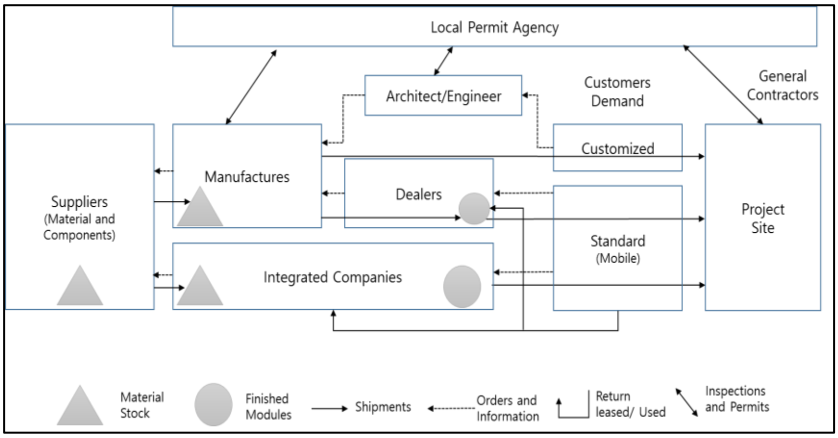


Figure 2-9. Supply Chain and Stakeholders of the Modular Building Industry (Adapted from SAID, 2014)

To sum up, the modular building construction market has been rapidly increasing in the last two decades. The previous modular building construction market focused on smaller scale projects, such as low-story(under fifth floor) residential buildings because of a customer's low confidence in modular buildings and technical challenges. By improving technology and customer's positive perspective of modular construction method, the modular construction market is getting growing and diversifying.

To deal with this market trend changes, manufacturing companies need more reliable tools to manage the various types of project and to serve the various customers' project requirements for detailed project duration considering current manufacturing abilities and on-site conditions. As a result, this research aims the development of planning and control model for applying various types of modular building construction project to project manager. Above all, developed model has to contain the several specific work activities' working conditions, such as resource variability and repetitive working environment. One of the reasons that modular building construction project not always performed in the same amount of work activities and fixed resources (number of workers in each work station and machine) used. The other reason is that, as mentioned above, modular units, which are consisting modular building's main structure, are performed in a repetitive working environment. For example, continuous production process consists of several work stations. The each workstation has their own working contents and labors to perform the specific work when modular unit is arrived at their stations. Considering the overall construction process in modular project, including manufacturing, transportation, and on-site installation, each phase's work activity performed specific working conditions as follows repetitive work. Thus, these characteristics have to reflect a model development strategy.

2.2 Research for Modular Building Construction Planning

2.2.1 Scheduling Methods in Modular Building Project

As mentioned above, modular building construction requires manufacturing production and on-site construction schedules (Figure 2-10). More specifically, the manufacturing production schedule is calculated by the total number of modular units for the project, number of production lines, number of workstations, and number of modular unit stock in the factory. On-site construction schedule is calculated by the daily number of modular unit installation based on crane lifting capability and possible to number of waiting modular unit at the installation site.

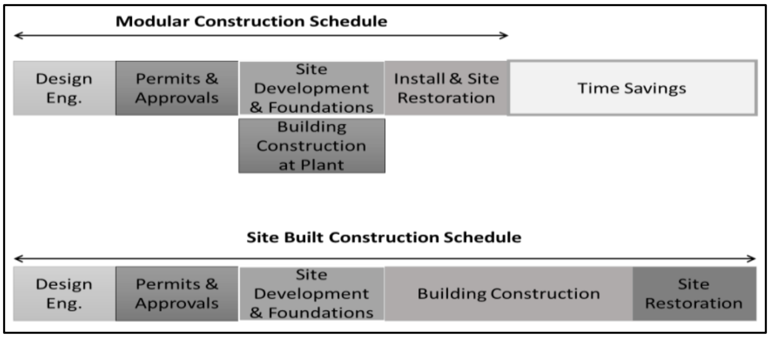


Figure 2-10. Typical Modular Construction Schedule (Adapted from Permanent Modular Construction, 2011)

To build a schedule in the project planning stage, the project manager mainly uses the following methods. Therefore, it is necessary to analyze the characteristics of these methods and examine their applicability to modular construction planning.

(1) Gantt Chart (Bar Chart)

It has been used the horizontal line formula bar graph comparing the planning and conduct by the display time of the particular period and the operation. Its advantage is easy to grasp the overall construction schedule and schedule of construction of each process and can be used without any special knowledge or experience because the visual clarity. However, if the precedence relationships between tasks are not clearly expressed, certain changes in the specific tasks that may occur during the construction process (planning against delayed or quick closure) occurs, predict the impact on the overall construction schedule with other work, which is difficult to assess the shortcomings (Figure 2-11)

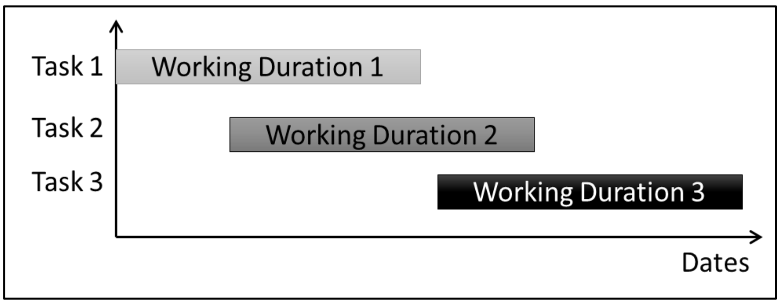


Figure 2-11. Gantt Chart Example

(2) Critical Path Method(CPM)

The CPM method assumes the entire construction period and the schedule to express the relationship between working time, including work on the network (Figure 2-12). This method is easy to solve the problem on the processes occurring in the work performed by the mathematical model and manage. Thus, through a certain calculation can determine the launching and completion of each task. In addition, it is possible to check the free time available to each job convenience to establish a work plan

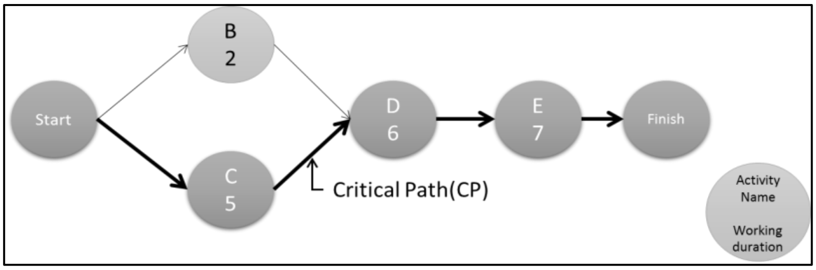


Figure 2-12. CPM Method Example

(3) Program Evaluation and Review Technique(PERT)

PERT is a process management techniques, which has been developed with the CPM. This method is similar to the CPM determines the duration of the construction work schedule and obtaining the critical path and choice (Figure 2-13). Significant difference between the two process control scheme is focused on an operation to be performed that is represented on the CPM network, but PERT focuses on the due date in these operations can be completed. A disadvantage of the more PERT is a constant depending on the calculated period of distribution of the work path, network, and increases the path to a coupling point to estimate the total construction period because it is the larger the error between the actual time.

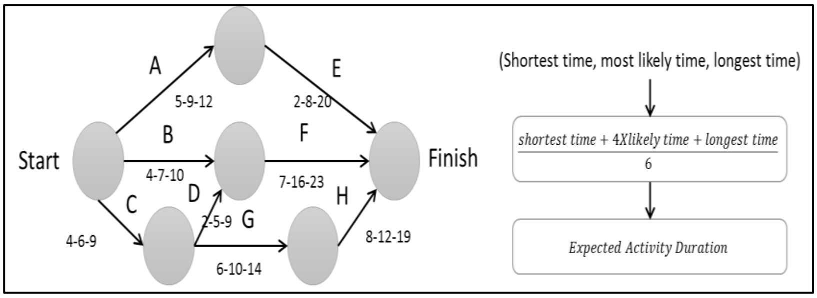


Figure 2-13. PERT Method Example

Consequently, these schedule methods are helpful to the project manager for developing the project schedule. For more precise, PERT (Program Evaluation and Review Technique) and CPM (Critical Path Method) are key elements of schedule network analysis (Larry,2002; Yang 2011;Chia,2013). According to this, schedule planning and management uses a mixture of both PERT and CPM considering its advantages and disadvantages (Table 2-2).

Table 2-2. CPM/PERT Methods Advantages and Disadvantages

Advantages	Disadvantages
Represent the work of the project activity as a graph	Difficult to reflect the schedule changes effectiveness in total construction project
Evaluate the time required to complete the project	Not considering resource constraints and dependencies
Grasp the operation of the most important effect on the finished project	Low efficient to use the buffer time
Identify which work activity is possible to delay without total project duration delay.	Difficult to reflect the different work activity's variations in the project schedule

2.2.2 Strategies for Modular Building Construction Operations

In the last two decades, a good amount of researches has been performed for modular building construction operations, such as schedule optimization (Abu Hammad. 2008; Wu et al. 2011; Olearczyk et al. 2009; Tam et al. 2001; Hasan and Al-Husssein 2010; Huang et al. 2011) and synchronizing with manufacturing production process and on-site work process (Briscoe,2005;Rodrigues,2010; Papadopoulou,2014; Moghadam, 2014).

There have been various researches related to manufacturing production scheduling optimization. Mehrotra (2004) suggests a systematic guidelines for the design of a layout for a manufactured housing production plant. This research argued that there is no standard method or procedure adopted to prepare a layout for modular construction. Abu Hammad (2008) developed the decision support system for improving the productivity of manufactured housing production through the selecting an efficient manufacturing layout. This research focused on removing the process bottlenecks and identifying the minimum operational times.

In the modular building construction schedule synchronizing with manufacturing production process and on-site work process researches, research problems and results have been focused on how to connect different processes following supply chain management principles.

Modular building construction process, one of the challenges in modular building construction managements, is how to manage the manufacturing production process (off-site products) for assembly at the on-site (Mullen, 2004). National Institute of Building Science report (2014) indicated that lack of collaboration between off-site and on-site construction schedule leads to difficulties in realizing the modular building construction benefits of schedule reduction.

With a perspective of conventional construction industry, modular building construction is one of the construction methods. Considering this perspective, modular building construction process derived from manufacturing, but its main construction work activities are same as conventional construction, so modular construction schedule has been developed by a fragmented view of specific contractor, which means manufacturing problems with each stage’s schedule variations only affects their own schedule. According to this, improving the schedule management for modular building construction schedule management skills researches have been focused on manufacturing production process optimization considering factory capability and on-site work installation productivity improvement by lifting crane location optimization. In this regard, the modular unit project manager has difficult to manage the modular building project following current perspective of conventional construction industry.

With a perspective of manufacturing industry, modular building construction has supply-demand relationships between manufacturing and on-site installation which is called as supply chain. In addition, modular building construction has both push-type production (make to Stock for supporting the continuous on-site installation and continuous production) and pull-type production (make to order considering on-site installation workflow) for Just-In-Time (JIT) and Continuous Replenishment Program(CRP).

The schedule planning and control of modular building construction not only need the effectiveness of manufacturing production process variations, but also effectiveness of on-site construction schedule variations in each other. From the perspective of a modular building project manager, however, this research classified modular building construction types can be divided into three categories for defining the scheduling strategies.

(1) Manufacturing Driven Project (MD)

Manufacturing Driven Project is usually called a single small scale project by the project manager. In the single small scale project, manufacturing duration is longer than on-site construction foundation work duration (Figure 2-14). In this type of project, stock yard size in the factory is enough to stock the total number of modular units for building the modular building construction project. According to this, the project manager has to perform the synchronizing the working duration both manufacturing production and foundation work for matching the production end date and foundation end date.

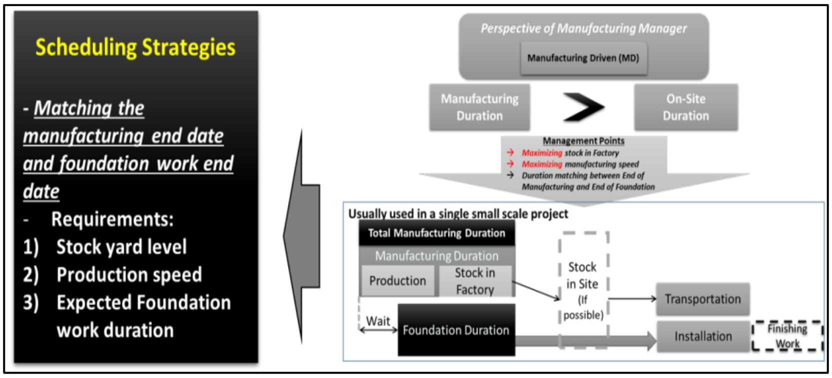


Figure 2-14. Manufacturing Driven Project Example

(2) On-site Driven Project (OD)

On-site driven project is usually called in a single large scale project by the project manager (Figure 2-15). In the single large scale project, manufacturing duration is shorter than on-site construction foundation work duration. Thus, unlike the manufacturing driven project, this project type has two schedule management characteristics about synchronizing purposes.

The first purpose is to minimize the production holding duration due to not meeting the dates between the date of the factory stock yard full with modular units and date of foundation work finish during the initial manufacturing. If stock yard full with modular unit date is earlier than the foundation work finish date, production has to stop until the end of the foundation work finish. In this case, productivity of reproduction can be a decrease compared with previous productivity because of difficulties for rehiring the worker and loss of work continuity.

The Second purpose is to reflect the daily on-site installation and daily manufacturing workability for producing modular units. After the initial manufacturing duration, project manager is concerned about how to synchronize the daily manufacturing production quantity and on-site installation work flow.

As noted above, modular building construction is less affected by the weather effect (rain, wind, temperature) because 60% - 90% of work activities were performed in indoor environments. Even though considering this advantage, unexpected production delay causes, such as strike, delayed raw materials delivery. In addition, unlike the manufacturing environment, on-site installation still performed in outdoor, which means daily installation workability is always possible to change. Accordingly, the project manager has to establish the what if scenario for handling this problem at the beginning of the project.

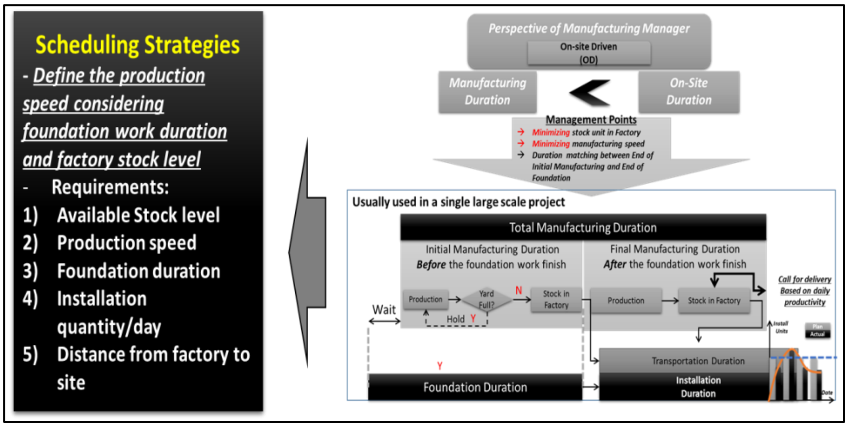


Figure 2-15. On-site Driven Project Example

(3) Combination Project (MD & OD mixed)

In a combination project, several different projects are executed at the same time. These projects have their own project duration like manufacturing driven or on-site driven. In this case, these projects have the same modular unit types, which means the same construction type (e.g., office, school, and residential) and different on-site installation sequences according to building design concepts (Figure 2-16).

As viewed from the project manager, each project sharing the same modular unit types and competitive for taking a modular unit to complete the project. To deal with this, the project manager has to make a plan for daily manufacturing production quantity and sequence of modular unit production based on several project information and constraints; total quantity of modular units, total project duration, on-site installation sequences, the capacity of the stockyard in factory and on-site. Unlike the manufacturing driven and on-site driven projects, its planning purpose is to keep the each project due dates considering manufacturing constraints and project constraints concurrently.

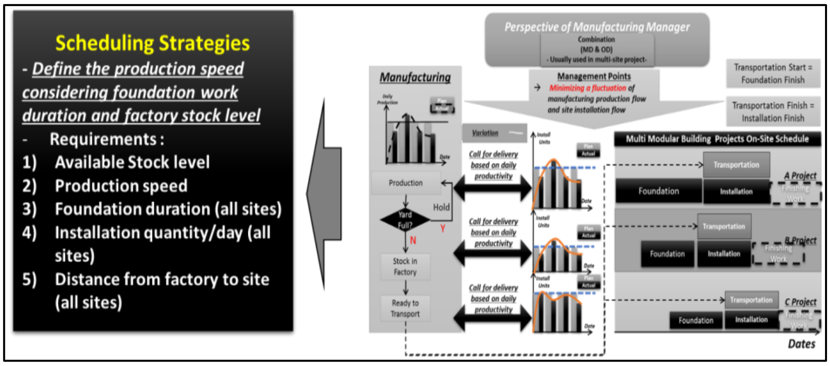


Figure 2-16. Combination Project Example

To sum up the three types of modular building construction project characteristics, the project manager needs several information to decide the optimal daily manufacturing production quantity and daily on-site installation quantity of each project type (Table 2-3). This concept is not same as conventional construction scheduling method because their working processes are not changed due to the project scales. For example, these schedules have fixed work activities (e.g., modular unit move to stock area, modular unit transportation from factory to site, modular unit assemble), which change only a few conditions, but do not change the work precedence in the entire schedule. This means that if reliable scheduling method or simulation tool exists, its reusability is higher.

Table 2-2. Summary of Modular Building Construction Project Type Characteristics

Contents	Single small scale project	Single large scale project	Multi-site project
The necessity of Resource Allocation	Low	Medium	High
Complexity of Activity Duration Calculation	Low	Medium	High
Possibility of Completion	High	High	Low
Importance of Factory Stock-Yard Area Size	High	Medium	High
Importance of Distance from factory to site	Medium	High	High
Possibility of Rescheduling during the construction	Low	Medium	High

2.2.3 Resource Optimization and Project Planning for Modular Building Construction

In Mathematics, computer science and operational research area defined that optimization is the selection of a better variable from some set of available alternatives (INFORMS Computing Society). In other words, it is to maximize the benefits of the manufacturing operation, while ensuring that resources are surely not exceeding any limits and satisfy as many of the requirements as possible.

From several optimization definitions, the optimization purposes have been focused on how to maximize the profitable value or to minimize the non-profitable value. Applying this concept to project schedule building, the resource optimization can be defined as maximizing the resource (labor, machine, material, equipment, etc.) utilization and minimizing the overall construction period for achieving the project completion profitably.

In this regard, resources and schedules optimization purposes are mainly focused on following six objectives (Tompkins,2003);

1) Minimize the make span of the schedule

2) Minimize the weighted completion time of each job

3) Minimize the total number of agents used to solve the problem

4) Minimize the amount of communication bandwidth used

5) If there is a value associated with assigning a task to a particular agent, maximize the aggregate value

6) If there is a cost (other than time) associated with assigning a task to a particular agent, minimize the aggregate cost

In the manufacturing industry, resources and schedules optimization purposes are focused on 1) minimizing the production time and costs and 2) maximizing the operation efficiency and 3) reducing the overall manufacturing costs (Giglio, 2002).

There are several several resources and schedules optimization methods used in the construction industry, such as time-cost trade-offs, resource-constrained schedule, and time constrained schedule (Ying and Li 1993; Li,1996). Li (1996) emphasized that resource optimization work should be performed sufficiently before the scheduling optimization work. To do this, resources and schedule optimization researches have been performed by using computer-aided techniques, such as Genetic Algorithms, Fuzzy set-based scheduling, Monte Carlo Simulation, Discrete Event Simulation, and Agent Based Simulation. Before the development of construction schedule optimizing simulation model, researcher should set a basic goal to optimize objectives. If the schedule optimizing goal was focused on maximizing the resource utilization, simulation model represents the resource-constrained scheduling optimization.

To accomplish these objectives, the project manager defines project constraints and performs resource optimizations that take into account current resource utilization levels. The project constraints normally defined as technological dependencies, capacity (equipment and employees), availability (material), and spatial aspects (safety or working areas) (U.Beibert, 2007). These constraints of scheduling problems are one of the variables for developing construction scheduling optimization simulation model. However, these constraints do not affect the resource and schedule optimizations to the same level in all projects. For example, in a modular building construction project, a yard capacity cannot be classified as a constraint if the yard stock level is more than the total modular quantity required. In the opposite case, however, the yard is one of the constraints in project scheduling optimization.

Therefore, in order to optimize the resource and schedule of the modular building construction project and construction operations, the project manager needs to be able to confirm which part is the constraint based on the project initial information. As a result, this research defines the construction simulation model for resource and schedule optimization as follows; the modular building construction project resource and schedule optimizations are not only to define what variables are constraints, but also to change the resource utilization and project constraint levels and find the reasonably various results of overall schedules when before a building the overall construction project schedule.

2.3 Theoretical Approach for Improving the Modular Building Project Planning and Control

2.3.1 Supply Chain Management in Modular Construction

Modular Construction is one of the construction methods, but it can be seen that it is closer to manufacturing in terms of project scheduling. Therefore, in the project scheduling stage, it is necessary to take into account the demand and supply side between the factory and the on-site installation, based on the concept of Supply Chain concepts as well as the consideration of the work connection and work precedence of the conventional construction.

The supply chain management definition and process have remarkably developed in the last three decades because of brilliant economic advancements, technology improvement, and lots of cross-industry service created (Gann,1986; MBI,2014). Within this flow, construction industry was fascinated by the manufacturing industry production process for improving project quality, reducing working time, and overcoming the shortage of workers. According to this, construction supply chain management researches have been performed in last few decades (Figure 2-17).

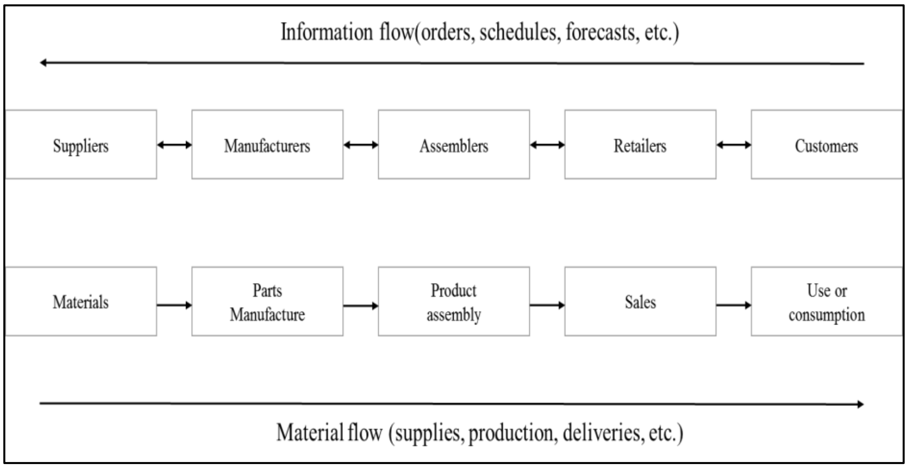


Figure 2-17. Generic Configuration of a Supply Chain in Manufacturing (Adapted from Vrijhoef, 2000)

Johnsonston (1995) defined supply chain management as, "….the process of strategically managing the movement and storage of materials, parts and finished inventory from suppliers, through the firm to customers." Following this definition of supply chain management, its aims focused on increasing the project execution performance and coordination of various process regardless of different production purposes.

Swaminathan(1998) consists that supply chain definition represents a relationship of working processes between manufacturer and customer based on two main processes; direction of flow of demand and direction of flow of product. To support controlling these flow, computer-aided simulation is efficient to check the schedule performance based on what if scenario in project schedule risks. Love et al. (2004) defined the construction industry's supply chain management considering current manufacturing industry experts' perception of supply chain definition. Following the research results, researcher defined the supply chain management as "… the network of facilities and activities that provides customer and economic value of design functions, contract management, service and material procurement, materials manufacture and delivery, and facilities management."

Supply chain management consists of two main phases; supply chain planning and supply chain execution. In supply chain project scheduling purpose is that forecasting the product demand and establishing the procurement plan and production plan for schedule optimization. The supply chain execution purpose is that managing the production flow for serving the product to customers on time. Within these two main phases common purpose is keeping a total project flow constantly and eliminating a non-valuable process.

Considering supply chain philosophy, the construction industry's main goals for applying supply chain are how to build an organization and manage the supply chains, which are resource information flow and material flow, to achieve a successfully finished the project (Table 2-4). To do this, Serpell(2004) emphasized that six distinguishing characteristics need to consider in applying supply chain management for the construction industry.

1) The construction product is for a single client most of the times
2) The product changes for each project
3) The place, equipment and methods of production change for each project
4) Not all the parts and materials can be stored on site
5) It is not easy to take advantage from economics of scale and learning

Table 2-3. Different Perspective of The Construction Industry and Manufacturing Industry (revised from Rocha, 2015)

Perspective	Manufacturing	Construction
Product	Components have a central role in the definition of the product architecture	Buildings combine components and spatial voids, which perform the most important product functions
Process	Suppliers deliver complex modules that are simply assembled by the main manufacture	Much work is usually performed on site, using traditional technologies

Supply Chain	The supply chain gets involved in the design and production of modules for a large number of products	Temporary supply chains usually have limited incentives to produce the same module for a large number of projects

These suggestions are helpful for the project manager, who needs considering supply chain management application for construction projects. However, its main concepts assuming that construction project consists several fragmented different construction works combined with single specific project schedule, so it is not perfectly same as modular building construction project. Modular building construction project works had connected with work precedence and durations following not only for completing a single project but also more than two different projects.

Within two different perspectives of looking at the supply chain, the modular construction method lies in the middle. Therefore, this research defines the scheduling direction considering the characteristics of modular construction based on the perspective of manufacturing and construction industries (Table 2-4).

Table 2-4. Defined Modular Building Construction Perspective Based on Manufacturing and Construction Perspectives

Perspective	Manufacturing	Modular Building Construction	Construction
Product	Components have a central role in the definition of the product architecture	Through a combination of independent unit or a unit receives recognized as a structure, and the project architecture exists in each unit.→Supplies and orders are performed on a module basis	Buildings combine components and spatial voids, which perform the most important product functions
Process	Suppliers deliver complex modules that are simply assembled by the main manufacture	The steel structure and floor of the module take factory first, and site installation process is performed by the conventional construction method → The overall process consists of pre-work for a production, production, transportation, and on-site installation.	Much work is usually performed on site, using traditional technologies

Supply Chain	The supply chain gets involved in the design and production of modules for a large number of products	The supply chain is defined as phase which the factory and on-site schedules interact with each other based on the three modular project types defined above →<u>The scheduling range will be set by the effects of unit supply and demand</u>	Temporary supply chains usually have limited incentives to produce the same module for a large number of projects

2.3.2 Lean Construction Principles

The lean concepts start from Toyota Production System, *lean manufacturing* (Ohno, 1988). Lean manufacturing focuses on removing the waste(defined by the performance criteria for the production system, Gregory 1999) in the production process and delivering the product to the customer at the right time.

From the first lean concepts introduced in construction industry, it is not directly accepted because manufacturing environment is different from construction environment. For example, manufacturing industry's final product, such as car, mobile phone, and computer memory cards, is made by same or similar design and production process, so it is possible to reduce the project schedules and costs easily following lean principles of removing waste such as idle time of non-value added work activities. On the other hand, construction industry's final product, such as building, bridge, and dam, has a unique design and construction process, so the construction industry's final products have more complex working relationships and high uncertain environments than manufacturing industry's final products (Howell,1999). Recently, One of the important lean principles is removing a waste in the production process. The waste is defined as performance criteria in the actual production process, which are incomplete to serve the requirements of the customer is a waste when it is time to make immediate and storage level still idle. Related to this, Birgisson, K. (2009) reorganized eight different types of wastes following lean theories based on Blucher and Ojmertz(2007) research results.

1) Overproduction: to perform more work or to perform the work earlier than needed
2) Waiting: for something to happen, for example, the materials deliveries to arrive or unexpected work activity delay effect shift to following work activity
3) Storage: to store more than what is necessary, such as to store materials on the building site
4) Motion: unnecessary movement when employees are performing their jobs, such as movements to retrieve the materials and tools
5) Rework: rework, adjustments and repairs that do not add any value to the customer
6) Overwork: to do more work than what the customer requires. The customer expects a certain level of quality, but more is not needed
7) Transport : unnecessary transport, such as relocating of materials

and equipment

8) Unused employee creativity: not to use the employee's full skill

For modular building construction project, these eight wastes also has been applied to make the reliable project schedule. For example, a modular construction project manager decides the daily production quantities of volumetric units at the beginning of the project considering factory production capacity and on-site installation capacity. During the project execution, however, schedule change variables, e.g, delayed raw material delivery to manufacturing and delayed installation time because of bad weather, affect planned daily quantities of production and installation. Also, if manufacturing production flow is faster than on-site installation flow comparing as planned flow, overall project schedule will be delayed because of the bottleneck effect (Moghadam,2014).

Thus, these wastes have to be removed or considered in project planning. To do this, project manager required tools or reliable project information to define the each work activity's wastes considering working conditions and to check the impact of wastes on the overall project schedule. Considering the lean theory based wastes, there are several characteristics can be derived from the relationships between wastes. In other words, these wastes do not occur independently and only affect themselves. During the project execution, for example, the overproduction, storage, and waiting wastes are highly connected within the overall construction process even though those wastes have their own specific reasons. The overproduction waste directly affect as planned storage levels and it is reason for holding a following work activity execution.

According to this, to develop the modular building construction project schedule simulation model, it is important to reflect both overall construction process interrelationships between work phases and each work activity working characteristics, such as different working durations and working conditions.

2.4 Research Methodology

2.4.1 Discrete Event Simulation (DES)

This research aims to development of modular building construction project scheduling model for supporting a project manager's decision about several different project scheduling options, synchronizing different schedules, reflect the schedule changes effectiveness in both manufacturing and on-site construction concurrently, and improving execution reliability based on repetitive work process. For this, it needs a reliable tool based on computer-added simulation method. According to this, this research adapted Discrete Event Simulation (DES).

Discrete-Event System Simulation Forth-Edition described the DES that "Discrete-event systems simulation is the modeling of systems in which the state variable changes only at a discrete set of points in time." DES has been widely used in various industrial area; manufacturing applications(Wu,1989; Spedding,1999; Detty,2000; Patel,2002; Sarjoughian,2009; Semini,2006;), construction engineering and project management(Smith,1995; Keller,2002; Lu,2003; Hubi,2011;Hong,2011), military applications(Page,1998; Hill,2001), logistics and supply chain(Lee,2002; Jung,2004; Manuj,2009; Idziorek,2010; Alzrajee,2012), transportation modes and traffic(Schmitt,2009; and business process simulation(Hlupic,V.,1998; Cheng,2004).

Matrinez and Ioannou (1999) investigated the fundamental conditions to use the discrete event simulation systems in the construction industry. This research was focused on comparing the effectiveness of tools for discrete event simulation CYCLONE and STROBOSCOPE. Both simulation tools are helpful to project manager for deciding project schedules. In addition, this research emphasized that the main purposes of discrete event simulation systems in the construction industry are process interaction (PI) and activity scanning (as). The PI is focusing on flow of entities, which have time-based resource moving and resource capture and release following conditions of entities. On the other hand, the AS is focusing on identifying various work activity's performance and work conditions whether working or not. Both approaches are useful to establish the simulation model concepts following purpose of simulation model development. If the purpose of simulation model development is focusing on manufacturing operation optimization, PI based simulation model is suitable. In addition, if its purpose is focusing on effectiveness of work activities' interdependent in particular systems, AS based model is suitable.

Birgisson, K. (2009) emphasized that DES application is not always helpful to build a project planning. Basically, DES possible to suggest the different project planning scenarios and it is easy to confirm the differences affects toe total project time and cost. To realize it, however, it needs definitions of numerous work activity's working conditions and all work activities' work precedence at the beginning of the model development. To overcome this disadvantage, it required that how to reflect the problems in simulation model and decide the level of simulation model details based on simulation purposes.

To sum up with, before the DES model development, researchers have to decide the simulation paradigms considering the research purpose. For this, more precisely considered the analyzing process, DES has three simulation paradigms; activity-oriented paradigm, event-oriented paradigm, and process-oriented paradigm as described in Table 2-6 (Moller,2014). First, an activity-oriented paradigm is consisted based on queuing system. This paradigm basically follows the random arrival time and a time gap exists between the arrival of jobs(Matloff,2008). In addition, it operates predefined circumstance (no state change) and shows predetermined action results. Second, the event-oriented paradigm is a classical simulation approach and is driven by the events. Each event has a corresponding simulation routine and it takes care of all changes that this event induces. If two events take place at the same time, they have to be sequential. Thus, this modeling style usually takes in a top-down view in each event. Finally, the process-oriented simulation models look at the system from the viewpoint of one entity. It means that one flow diagram with explicit time consumption.

Table 2-5 The Classification of Discrete-Event Simulation (revised from Moller,2014)

Simulation Types	Contents
Event-Oriented Simulation	Based on time-dependent and restricted event-handling language elements
Process-Oriented Simulation	Based on activation trigger of the following events as specified language elements
Activity-Oriented Simulation	Based on activity schedules that are started if specific constraints are fulfilled

Discrete event simulation has been used in the construction industry to develop the process behaviors and what if scenarios based on limited project information. To support this, there have been various construction simulation programs introduced as described in Figure 2-18 (Jarkko, 2013);

UM CYCLONE, STROBOSCOPE, ABC, Simphony.net, Risim, and SDESA.

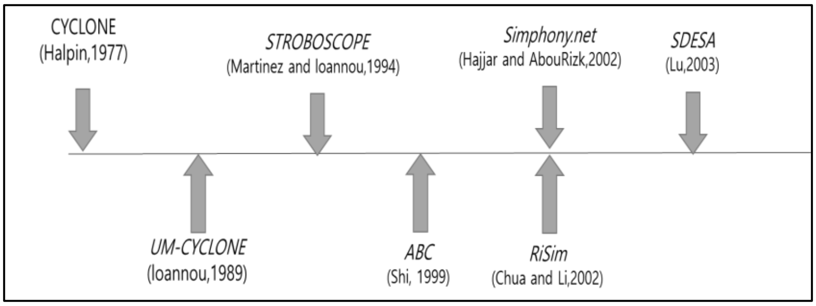


Figure 2-18. History of Discrete Event Simulation Programs in Construction Industry

All these simulation tools try to reflect characteristics of the construction process (work precedence and resource availability) and working environment (unpredictable delay risk, affected by random factors of heavy machine status and weather conditions) in developed simulation models. In general, those discrete event simulation tools in construction industry researches have been focused on process-oriented simulation concepts as described in Table 2-7. The main reasons that these computer simulation tools provide following three main advantages; modeling resources, dynamics, and randomness.

Table 2-7. DES Advantages using Computer Simulation Tools (revised from Shi, 1999)

Contents	Descriptions
Resource Modeling	Many important characteristics of resources can only be modeled through simulation technique, including: 1) active role of resources in performing construction operations; 2) relationship between the actual construction progress and the involved resources, such as different productivity of equipment capacity; 3) resources shared simultaneously by multiple activities.
Dynamics	A construction operation is a dynamic process involving the dynamic interactions between activities/processes and between activities and resources. No any other tool is able to model the dynamic behavior of construction operations.
Randomness	A construction operation is affected by many random factors such as operating status of equipment and weather conditions. Only

	the simulation technique enables these considerations to be incorporated into construction planning

To sum up, DES provides an alternative method for construction project scheduling based on the real construction system. The CPM/PERT methods have been used to calculate the total construction project durations following calculations by other calculation methods applied. In while, DES not only serves a total construction project duration considering each work activity’s uncertainty of work durations but also shows what-if situations (schedule delay) affect total project duration.

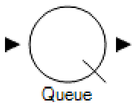
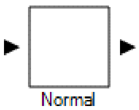
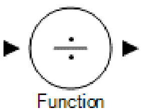
Therefore, this research uses Discrete Event Simulation concepts for developing the modular building construction resource and schedule optimization model. More precisely, this simulation model structure is developed by the activity-scanning oriented approach based simulation tool because of reflecting repetitive works in modular building construction characteristics and providing work activity condition change effect to modular building project manager. Also, this simulation method to be implemented to represent the overall modular construction process, as well as working characteristics of the modular unit.

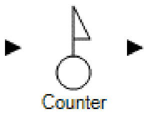
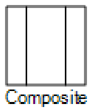
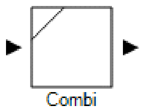
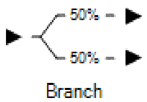
2.4.2 CYCLONE Simulation

This research used the CYCLONE (i.e., Cyclic Operation Network) simulation tool for making a modular building construction schedule optimization. The CYCLONE tools developed in 1997 by Halpin and it is one of the activity-oriented simulation tools in discrete event simulation types.

This tool uses seven elements (Queue, Normal, Function, Counter, Composit, Combi, and Branch) to build a simulation model and its main descriptions as described in Table 2-8. Basically, the elements that comprise the CYCLONE simulation have the purpose of refining and modeling the work of one entity. For example, if the “Truck” is an entity in Earthwork, the only detailed work in this entity is to create a single loop model with a combination of the elements. Therefore, the simulation model that constitutes the “Truck” entity cannot represent other entities of Earthwork, such s “Backhoe” or “Excavator”.

Table 2-8 Descriptions of CYCLONE Simulation Elements (revised from Tang, 2004 and user guide for cyclone template at symphony.net 3.5)

Elements Name and Symbols	Descriptions
Queue 	Representing the waiting or idle state of resource entities; sometimes, the QUEUE node also acts as a GENERATE node to clone resource entities by the number as specified (i.e. N). Unlike work task (Normal), a QUEUE release only one unit at a time. If one unit is available and all following COMBI's are ready to receive it, then the unit goes to the COMBI with the lowest level.
Normal 	Unconstrained in its starting logic and indicating active processing of resource entities.
Function 	A number of resource entities as specified (i.e., N) are cloned for a GENERATE Node, or accumulated and merged into one resource entity for a CONSOLIDATE Node

Counter 	Counting the number of resource entities passing through it.
Composite 	A container other elements that allows a modeling hierarchy to be created.
Combi 	Constrained in its starting logic, otherwise similar to the normal modelling element.
Branch 	Accepts any real number between o and 1 as a probability. The value entered is assigned to and reflected at the top branch of the element.

Even though CYCLONE represents one of the activities-scanning purpose simulation, however, it is possible to make a multiple processes and to connect these processes using Queue element and Function element (Figure 2-19).

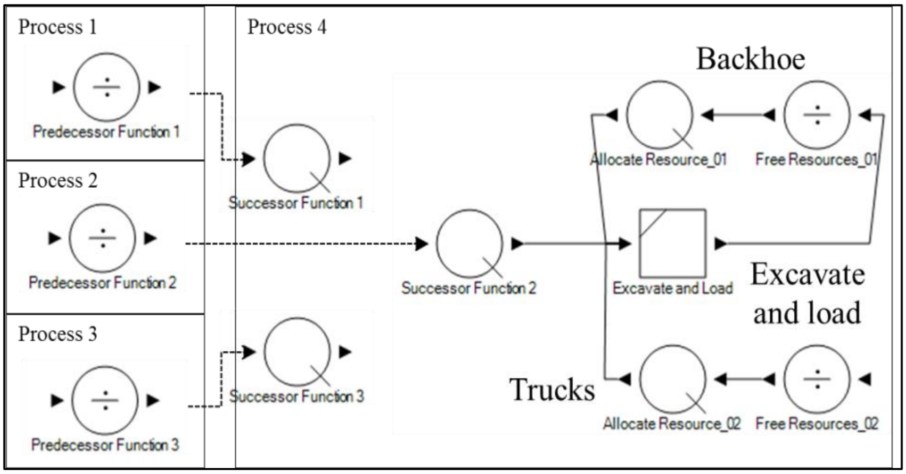


Figure 2-19. Multiple Predecessor Process (adapted from Sawhney,1998)

The CYCLONE requires an input data (each work activity) to activate the Combi and Normal elements and the number of resources in Queue element. When this program was first introduced, a model developer requires professional knowledge of computer language, such as JAVA, Visual Basic, and C++, to reflect detailed work activities' conditions and input data implementation of the simulation model.

This part is one of the barriers to develop the model and to apply for real project using CYCLONE (Figure 2-20). Recently introduced software, Simphony.net 4.0 version, however, provides a wide variety of work activities properties implementation was easier than first introduced CYCLONE simulation tool. For example, a model developer wants to set the parameters before the model development, it requires numerous parameter setting based on the Visual Basic language. However, current simulation tools provide simple user-interface to set the parameters based on model development purposes. According to this, although after 30 years have passed since CYCLONE simulation was introduced, it still useful to build a repetitive work environment project schedule planning, like a modular building construction project.

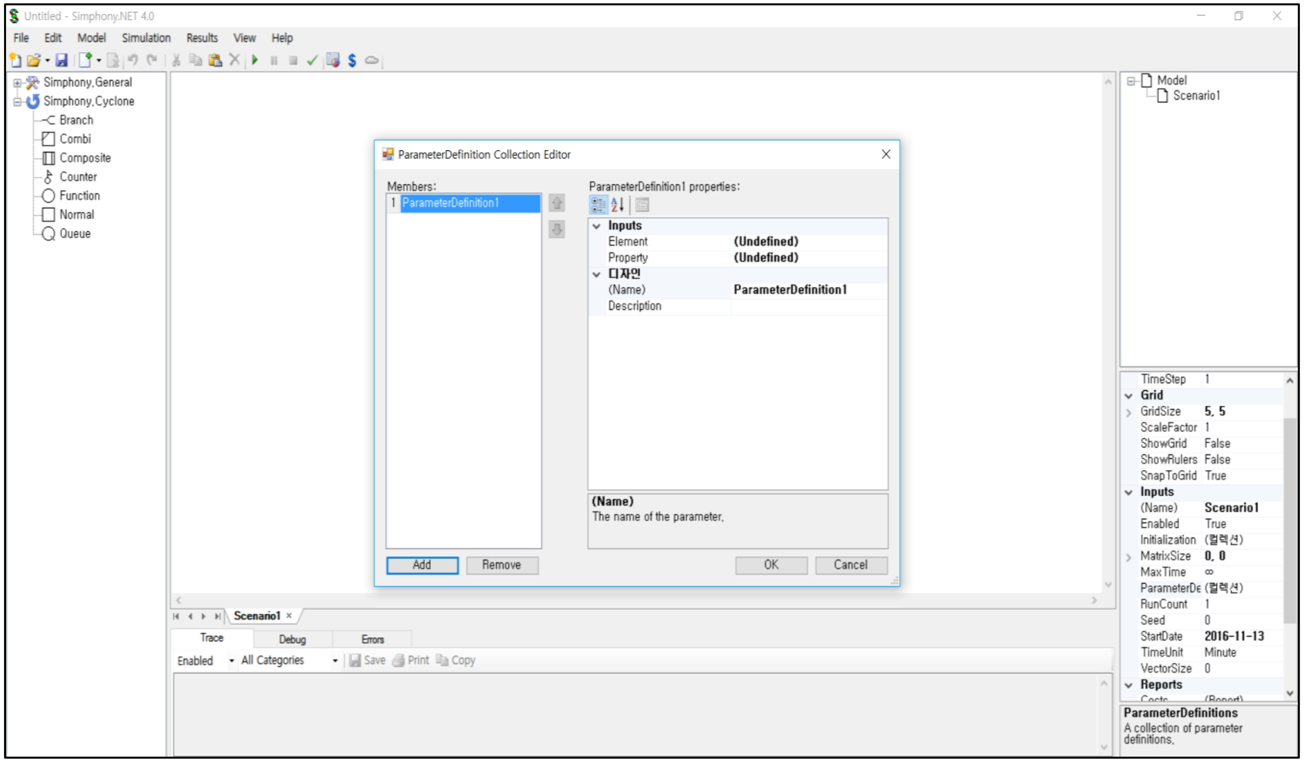


Figure 2-20. Example of Simphony.net.4.0 Environment Provides CYCLONE Simulation Parameter Setting

2.5 Summary

This chapter first investigates the definitions of modular building construction and the characteristics of a construction process and structure types. Then, performed the modular building construction market change analysis for defining current modular building construction project planning and execution problems relating a current scheduling methods' limitations. Current scheduling methods, like as CPM/PERT, have been widely used to build a modular building construction project. These methods have both advantages and disadvantages to build the overall modular building construction project schedule. There are two main problems in current scheduling methods. First, these methods are difficult to reflect the different work activity's variations in the project schedule. Second, these methods are not considering resource constraints and dependencies. According to this, this research found that current scheduling methods are insufficient to reflect the modular building construction project.

Next, this research investigates the modular building construction project scheduling strategies and defines the scheduling optimization purpose. To define the scheduling strategies, this research classified modular building construction types can be divided into three categories for defining the scheduling strategies; manufacturing driven project, on-site driven project, and combination project. Following these three categories, this research defines the scheduling strategies and requirements for developing modular building construction project schedule results. By applying the scheduling strategies, this research investigates the schedule optimization definitions and sets the research definition of modular building construction project schedule optimization.

After the research for modular building construction, this research analyzes the Supply Chain Management and Lean construction principles in modular building construction. According to this, this research sets the theoretical structure for developing the modular building construction project schedule optimization methodology by Discrete Event Simulation (DES). Considering characteristics of DES, the Cyclic Operation Network (CYCLONE) was selected for development of the modular building construction project schedule optimization simulation model. The CYCLONE includes several elements (Queue, Normal, Function, Counter, Composit, Combi, Branch) to build a simulation model.

Chapter 3 Overview of Model Requirements and Simulation Model Development

This chapter performed development of schedule optimization model for modular building construction project. This simulation model mainly consists of four parts; pre-work for production, production, transportation, and on-site installation. After the simulation model development, performed the each simulation module's verification based on actual volumetric modular building construction project information.

3.1 Strategies for Developing Simulation Model

3.1.1 Comparison of Conventional Construction and Modular Construction Project Planning and Control

As above mentioned, conventional construction industry's schedule methods, such as CPM/PERT, are helpful for calculating total construction duration and each work activity's duration considering work precedence and relationships of work activities. In addition, these methods provide the project schedule variance information through the comparing planned schedule and actual schedule. Although these methods have several advantages for building a schedule, there exist following requirements for developing modular building construction operations.

1) A modular construction project schedule needs efficient scheduling methods for reflecting repetitive construction work. Except partial use of modular construction method and fully customized project for modular building construction, common modular building construction projects have been performed in a factory production line according to planned repetitive work activities. In general, repetitive work, such as building construction's finishing works, road project, and tunnel project, consists of fixed working methods (working sequence) and flexible number of several workers and heavy machines based on daily construction work quantity. From a broad perspective of construction project managers, all construction works represent repetitive work because all construction work activities need a similar procedure to finish the work; each work activity performed in their own procedure by specific material, work procedure, and workers. Modular building construction project, repetitive work definition is similar to conventional construction because of the characteristics of the manufacturing production

process. To build the repetitive work scheduling, various researchers emphasized that current CPM/PERT scheduling methods difficult to express the detailed each work activity's work location and time relationships and to manage the labor(worker) resource during the project planning and execution. (Reda,1990; Moselhi and El-Rayes, 1993; Harmelink,1995; Fan,2006; Cho,2010). To overcome these limitations, Line-Of-Balance(LOB) method and Linear Scheduling Method(LSM) have been introduced, but these methods still exist following limitation. These two methods assuming that all resource utilization and effect of the learning curve phenomenon are maximized. To build a project schedule, these two main ideas have to consider to make an ideal schedule base line. For maximizing these two assumptions implementations, modular building construction project manager, who has responsibility of managing from manufacturing to on-site installation, need many previous similar project data for calculating the resource variance risk and defining level of learning curve effect. Considering modular building construction history, from begging in of the well equipped with modern facilities, there are not enough to build a general schedule baseline to use the different project conditions.

2) The modular building construction, especially volumetric modular construction system, requires several schedule options to deal with schedule change problems. Modular building construction project schedule changes significant problem of keeping a project duration. The schedule changes affect total project duration changes not only conventional constructional project, but also modular building construction project. Considering both project types, however, there are different countermeasure about schedule changes. Within use CPM method of conventional construction, its mainly focus on work activity's work duration that exists in Critical Path (CP). The CP represents that the longest sequence of work activities in the planned project and determines the shortest time possible to complete all works in the work precedence network. In other words, Non-CP work activities' schedule delays do not affect significantly total construction project completion dates. The characteristics of CP that there is only single CP exists in a single project. As above mentioned, CP is represents the longest duration of a project following definition of CPM. Thus, schedule changes occur during the project execution, project manager firstly check the work activity's location, whether it's included in CP or not. If one of the CP's work activity duration

change happened, total project schedule will be extended. Therefore, the project manager has to make a plan for recovering work activity's extended work through the throw in an additional resources or overtime work considering other work activity's work relationships. In addition, it is not fixed during the project execution because planned Non-CP work activity duration changes affect significantly CP network changes. Following precedence of the work based network scheduling on a construction project, unforeseen circumstances cause estimated Non-CP work activities' durations to change. According to this, the project manager has to observation of the schedule delay effect to all work activities. Within use CPM method in the modular building construction project, these two CPM's characteristics are one of the reasons for establishing a low-confidence modular building construction project planning and control base lines. For example, if the schedule changes occur during the project execution because of delayed on-site installation, within a CPM based scheduling project, project manager checks the schedule change's impact following overall current schedule. To check the total schedule change impact, there are several schedule impact analysis techniques can be used; a) global impact analysis, b) net impact approach, c) adjusts as-planned CPM approach, d) adjust as-built CPM approach, e) collapsed as built schedule approach, f) modification impact analysis approach, and g) time impact analysis approach (Arcuri,2007), and except a) and b), remaining techniques uses CPM. These remaining techniques assuming that schedule change impact only affects total construction durations which means its results are not relative to the resource usability and total construction work productivity. According to this, modular building construction used in the CPM schedule project is difficult to confirm the resource (labor, machine, material) utilization effects.

3) There are two reasons for the modular building construction project manager requires a schedule reliability checking system to decide schedule baseline within a short time. First, in general, from the perspective of the customer, the modular building construction method is one of the construction method. According to this, modular building construction always comparison with conventional construction method. To decide whether modular building construction method use or not, the customer requires a manufacturing company to project schedule which is the total project duration. To respond to this requirement,

manufacturing company preparing a document which is the current production capacity and given project information based data for comparison with conventional construction method. With CPM, however, manufacturing company is difficult to handle this information because CPM only provides single determined project duration one at a time, so schedule uncertainty based results did not provide.

Second, one of the most advantages of modular construction method is that total project duration is shorter than conventional construction project because of concurrent construction work processes with manufacturing and foundation work. To achieve this advantage, the project manager needs a plan for the daily production quantity and on-site installation quantity following limited project information at the beginning of the project. In general, project manager calculates these quantities based on the simple mathematics method, such as total number of required units and planned maximum daily production quantity are results of daily production quantities, then make a total production schedule based on CPM. As described in the first sentence in this paragraph, modular building construction schedule required two main schedules (manufacturing and on-site construction) to realize a reliable project planning and execution. Considering the work activity's performing process, manufacturing phase needs duration calculation method for considering work capacity in each work station and reflecting continuous working condition based total production durations, such as currently having another project numbers or fixed durations for preparing a new project. These conditions, however, are not directly connected in CPM because CPM only represents work activities' determined durations which means it is not a method for deciding total project work activities' duration calculation based on various what if conditions, but method for showing total work activities' work relationships and fixed working durations. According to this, modular building construction project managers need two steps for making a project planning and execution; calculating each work activity's duration based on specific methods or historical data and connecting work activity's work precedence based on CPM. Considering modular building construction process, the project manager is suffering from making a schedule considering comparing two different schedules' relationships concurrently.

3.1.2 Detailed Strategies for Developing Simulation Model

1) Pre-work for Production Phase

To develop the modular building construction operations simulation model, it needs defined the several requirements. This research adapts volumetric modular building construction process, so the overall simulation model developed based on these types of construction process and work activities. As described in Chapter 2, volumetric modular building construction process has work environment characteristic which performed 60 - 90% construction work activities in the factory. To make an each modular unit, modular unit production factory needs resources, such as labor, material, machine, like as conventional construction. Before the starting to make, volumetric modular unit needs pre-work for the production process to build a common steel structure and floor products. Within the pre-work for production process, there are mainly two different works needed; structure assemblies and floor assemblies. These two works not performed in the main production (inside the factory), but performed in other working space in the factory (outside the factory) because of its working durations. Both structure assemblies and floor assemblies required more than one day to make a each completed product. For example, if floor assemble work made with steel structure and concrete, it contains several work activities and precedence; floor structure assembles, rebar placing, concrete pouring, leveling, wait to consolidate, check the quality. These working duration cannot synchronize with overall main production working duration in each work station (50 minutes or 1 hour constantly). According to this, pre-work process simulation has to separate from main production process simulation module and its work requirements should be reflected in the model.

2) Production Phase

On overall manufacturing process, this research focuses on continuous production process. The continuous production process requires working times to implement overall work stations. For example, if the project manager decides 50 minutes working and 10 minutes break time, it will be applied to all workstations in the same manner. This concept is derived from manufacturing industry working types, like automobile manufacturing. To do this, however, manufacturing companies need to have a certain level of automation facilities. Otherwise, this work schedule is difficult to maintain because the work capacity of the workers cannot always be kept the same as expected workability and it becomes one of the bottleneck causes. Therefore, to implement the continuous production process in modular construction, the project manager should be able to change the work time setting, and the user-interface is needed to check the overall production productivity change based on changed work time.

3) Transportation Phase

The manufactured modular units are moved through the transportation means. There are several transportation means, such as land and maritime transportation. In general, volumetric modular unit is heavy and large, so it usually used land transportation; truck, trailer, and rail. There two main characteristics exist in land transportation. First, it is necessary to determine the total number of vehicles required for project execution considering both factory production schedule and field installation schedule. Second, there is a safe operation speed level to prevent damage of modular unit. These two conditions are requirements that apply to all situations regardless of the size of the modular building project, so project manager has to create a transportation schedule considering these two conditions. According to this, the transportation simulation model requires these two conditions' changing effect analyzing module.

4) On-site Installation Phase

To finish the modular building construction project, on-site installation work is needed. As mentioned above, modular building construction projects using volumetric modular units' field work is less than manufacturing work. Therefore, the complexity of site work is low compared to conventional construction project. Instead, a crane (truck or tower) is mainly used for the installation work, and a worker is required to assemble the unit at the planned position. These two resources (crane and worker) directly affect production productive as well as filed productivity. If the planned productivity of both resources is not achieved, the manufacturing production and transportation plan should be changed. This is the bottleneck effect in manufacturing industry. Manufacturing industry refers to subsequent process impacts due to prior process delays, but also from subsequent processes in a modular construction project. Thus, the project manager has to decide appropriate work activities' working durations in crane operation and installation work considering the overall project schedule. According to this, on-site simulation model requires these two resources working conditions changing effect analysis model. To explain the characteristics of each phase's work activity, this research described a single process as a single Node and explains the characteristics of the work activities into the each Node (Figure 3-1 and Figure 3-2).

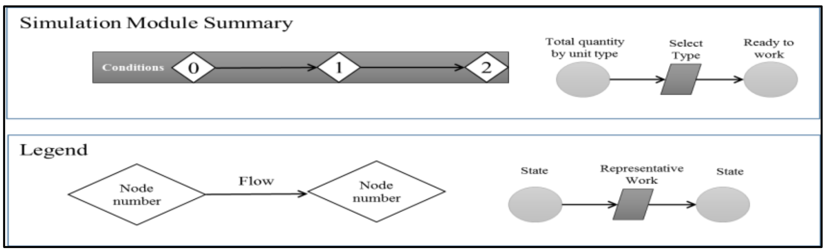


Figure 3-1. Simulation Model Description and Legend

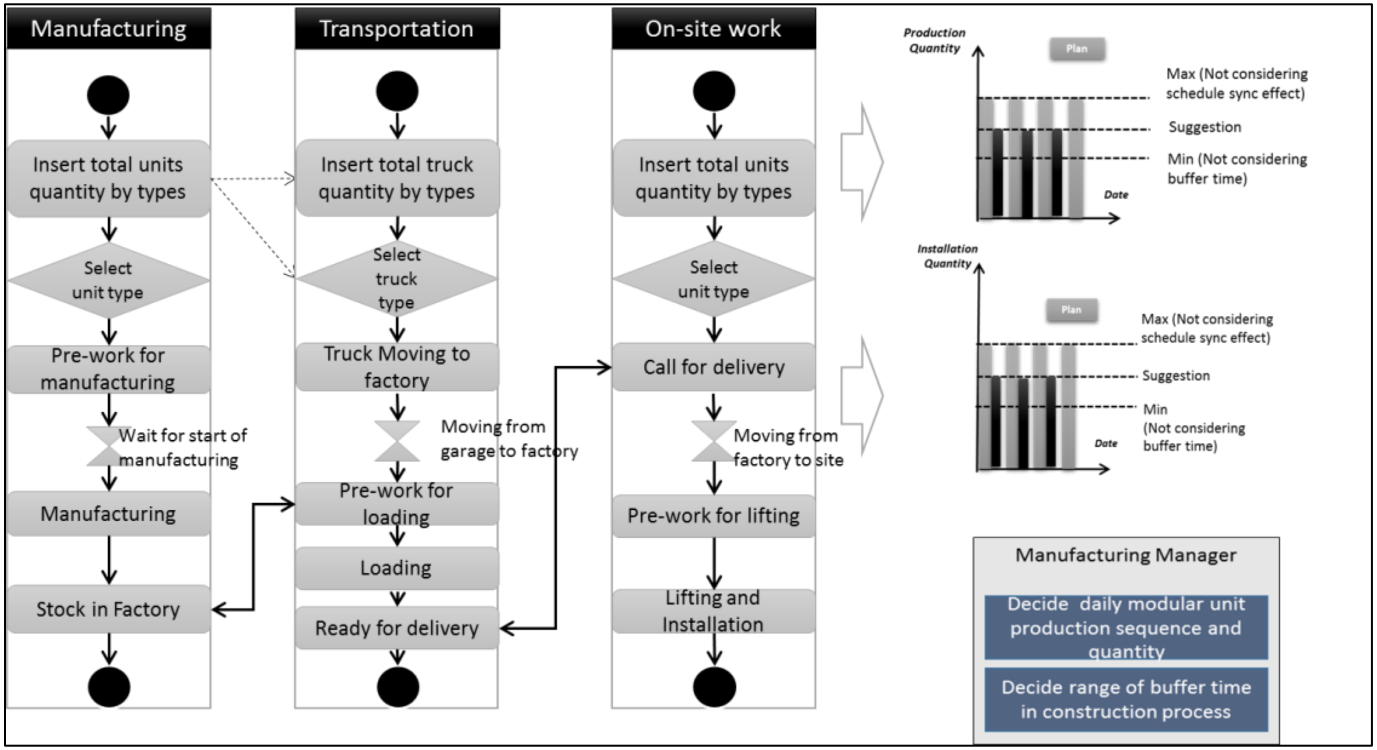


Figure 3-2. Overview of Concept for Simulation Model Development

In Figure 3-2, it summarized the basics necessary for the implementation of scheduling volumetric modular building construction project. Based on this information, a conceptual simulation model using CYCLONE is shown in Figure 3-3. This model has four different simulation modules; manufacturing, foundation, transportation, and on-site installation.

First, the manufacturing simulation module consists of several elements of the total number of units, manufacturing work duration, and work stations' working limitations elements. These elements will be divided into several work activities in the detailed manufacturing simulation module.

Second, the foundation simulation module consists of total quantity of foundation work, foundation work duration, and foundation work resource limit elements. Unlike other simulation modules, this simulation module will be composed of simple work activities. In general, in order to carry out the foundation work in the conventional construction work, a lot of work and resources are needed and it is necessary to reflect it in the model. The modular construction is not much different from the conventional construction, but the main focus of in this study's simulation model is to determine how a typical level of work schedule is linked to the factory production schedule and how the work delay affects the overall schedule.

Third, a transportation simulation module consists of the total number of truck, truck limit, and transportation time elements. These elements values will be set based on basic project information. Finally, the on-site installation simulation module has a crane lifting and assembly work elements. These two main elements have resource constraints and working duration variance based on historical data and specific project information.

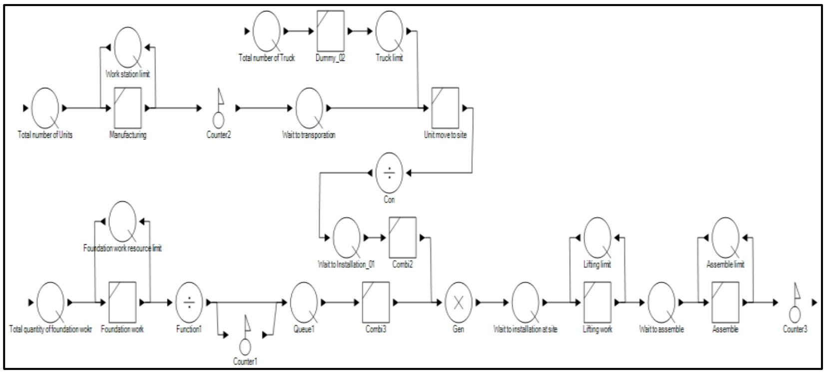


Figure 3-3. Overall Conceptual CYCLONE Simulation Model for Volumetric Modular Building Construction Project Planning

3.2 Model Development

3.2.1 Phase 1 – Define the Work Activities at Each Phase

1) Pre-work for production

Before the mainly working on the production line, modular units need additional construction works. The additional construction works contain mainly structure assembly work and floor assembly work. These two works not always needed, but most of volumetric modular units required these two works because of increasing structure strength and satisfying regulations of floor noise. These two works require a large space for working and take a long working day, so it is difficult to perform in a production line. Therefore, these two works performed in extra space in a factory or available space for working nearby factory.

2) Production

Each workstation has its own detailed work activities and shares work and break times. As described in 3.1 sections, most factories producing volumetric modular units are low compared to automation facilities in the manufacturing industry, making it difficult to maintain a single working time and break time. The one of the fundamental solution is to install more automation devices and to match the work level of individual workstations in the same. However, this problem-solving method does not directly affect the effective scheduling for the current project implementation since it requires time and cost. To overcome this problem, the project manager needs several scenarios for the possibility of work completion depending on the work time and break time variability of each workstation.

3) Transportation

The main purpose of the transportation simulation model is connected between manufacturing simulation module and on-site installation simulation module. In general, project manager determines the total number of transportation vehicles required based on the total number of units and ability to transport a single vehicle. After that, the number of vehicles determined is recalculating considering distance from manufacturing to on-site installation and total working hours limit.

One of the transportation simulation model considerations is that if transportation delays occur during the transportation, how much its impact affect planned manufacturing production flow and on-site installation work schedules. In the manufacturing industry, transportation is the last step in supply chain management. Its main purposes are how and when to get raw materials or finished products deliver to destination. The modular building construction project is also similar to the transportation purpose of the manufacturing industry. However, in a modular building project, transport is one of the factors that determines both the speed of production and the speed of on-site installation, as well as delivering manufactured products to the destination. For example, if the transportation delay effect is not taken into consideration, the level of stock at the factory will reach the maximum capacity and it is reason for decreasing a production flow. In addition, if the on-site installation schedule is delayed due to delays in transportation, the final construction due dates will be extended.

4) On-site Installation

The on-site installation is the last simulation model in modular building construction scheduling simulation. As described in Chapter 3.1, on-site installation working environment is not same as manufacturing working environment. For example, unlike the manufacturing work environment, on-site installation works influenced by weather, such as wind and rain. If the wind speed exceeds the working condition of the crane lifting work, the whole process will be stopped even if the production and transportation are normally performed. In addition, the rain does not affect the manufacturing work, but in the on-site installation, the work will be delayed for the waterproofing work of modular unit, so whole prices have to stop.

Accordingly, to set the each work activity's working duration at the on-site installation phase, the project manager sets a certain level of buffer time in the installation process to reduce the delay in the on-site installation work. To support it, this research provides an on-site installation module that can be used to determine the effect of installation work on the individual work time range as well as on the manufacturing and transportation scheduling

3.2.2 Phase 2 – Developing a Conceptual Model Based on Work Relationships

1) Pre-work for Production

As described in Figure 3-4, Before the Node 0, the project manager has to set the total modular unit quantity of each modular unit type. Except single modular unit uses house or office or retail shop, modular building consists of several different modular unit types' combination. Calculating a total modular unit quantity is performed by designer who designed the overall modular building structure.

Node 0 represents the module type selection. In this step, project manager decides which unit type has to do at first. In general, this sequence decided by on-site installation sequence because of preventing a unit delivery error. Considering raw material delivery and level of work difficulty, however, it is possible to make a specific type of unit with priority.

Node 1 represents the structure and floor assembly works. As described in Chapter 3.1, these works needed specific working durations to finish the works. The "Structure Assemble" and "Floor Assemble" are work activities in overall pre-work for production, which are need a resource of H-beam and work activities such as erection, bolting, leveling, and concrete pouring. If these works not performed, it can be set the non-value work in pre-work for production.

Node 2 represents the combination of a floor structure and a main structure. In general, at Node 1, the floor structure and the frame structure have different working hours and the maximum workable amount. Therefore, in order to combine these two structures in Node 2, it is necessary to reflect time constraints and constraints of total number of combinations at the same time.

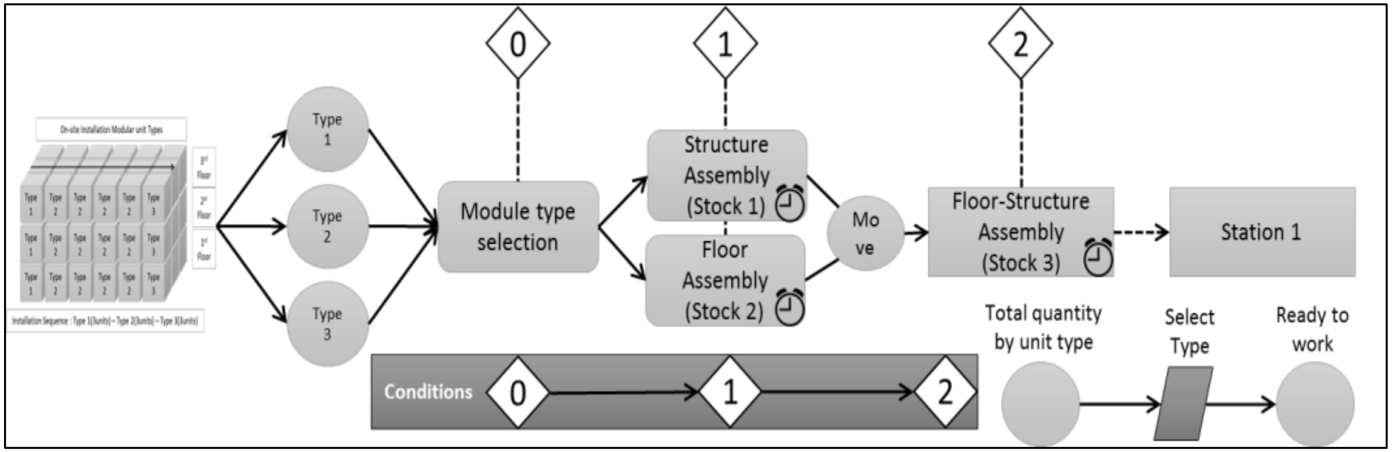


Figure 3-4. Conceptual Work Activity Groups in Pre-work for Production

2) Production

Modular unit factory production process normally consists of nine steps; floor Conc'c manufactured, steel structure assembles, wall panel installation, window installation, electrical wiring, equipment pipingwork, exterior finish, packing, and shipments (Figure 3-5).

In Figure 3-6, the Node 3 represents the working environment of each workstation. It mainly includes the working time and breaking time that are given in advance, and the number of workers. To set the resources in the simulation model, each workstation has individual working environment (time, resources) setting module and has working conditions setting module (whether it can work or not). In the real world, every workstation contains several different detailed work activities, which have work precedence relationships and specific number of workers.

To optimize the production line process or improve the production, productivity, these detailed work activity's information has to consider in developing the simulation model. In this paper, however, the main purpose of simulation model development is how its working condition changes affect overall project scheduling results from manufacturing to on-site installation. To do this, though activity-scanning modeling method implicated in this research, information on the details of individual workstations is not necessarily reflected.

This is because, in the continuous production method, the work method is already modeled as one of the overall project constraints on productivity and the maximum number of the available workers. This is because, in the continuous production method, the working time and the maximum available worker number are already modeled as one of the constraints of the entire project. The Node 4 represents the manufactured modular unit's moving. After Node 3 works completed, modular unit moved by forklift from last work station to stock yard.

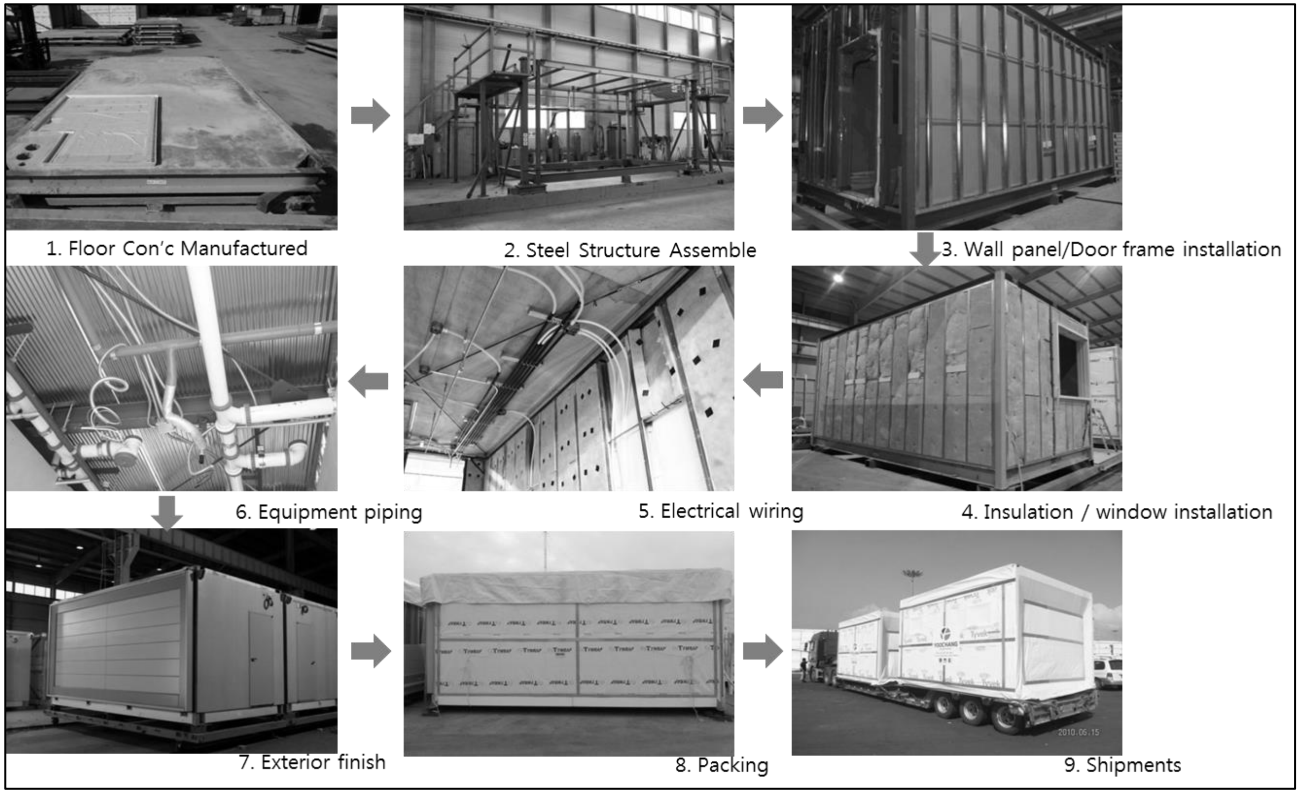


Figure 3-5. Modular unit Factory Production Example

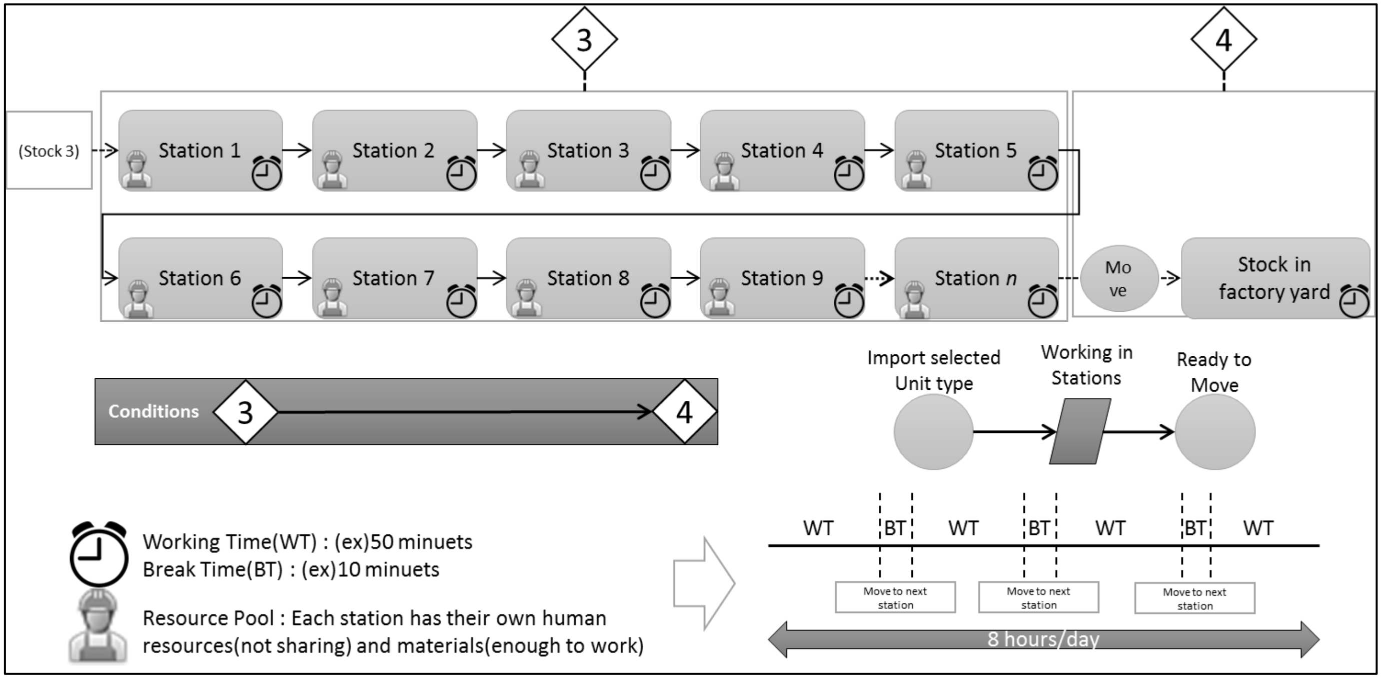


Figure 3-6. Conceptual Work Activity Groups in Manufacturing Production

3) Transportation

As described in Figure 3-7, Node 5 represents the work activities of vehicle moving from the garage to factory and loading works at the factory storage area. Node 6 represents the vehicle's waiting for unloading work at the on-site installation. When the vehicle arrives at installation site, there are two working conditions required; there is no vehicle loaded with a modular unit at the site, and lifting crane should be ready for operation.

When both these conditions are satisfied, the vehicle can enter the site. It leaves the site at the beginning of the crane lifting. Node 7 represents the vehicle return conditions. This means that if the total vehicle driving time exceeds the maximum driving hours of one day, the vehicle returns to the garage or, if not, returns to the factory. However, the CYCLONE simulation only provides a probability selection service(Branch) for choosing a what if the cases. Therefore, when developing the transportation simulation module, the probability of returning to the factory and the garage is fixed by fixing the probability in simulation module.

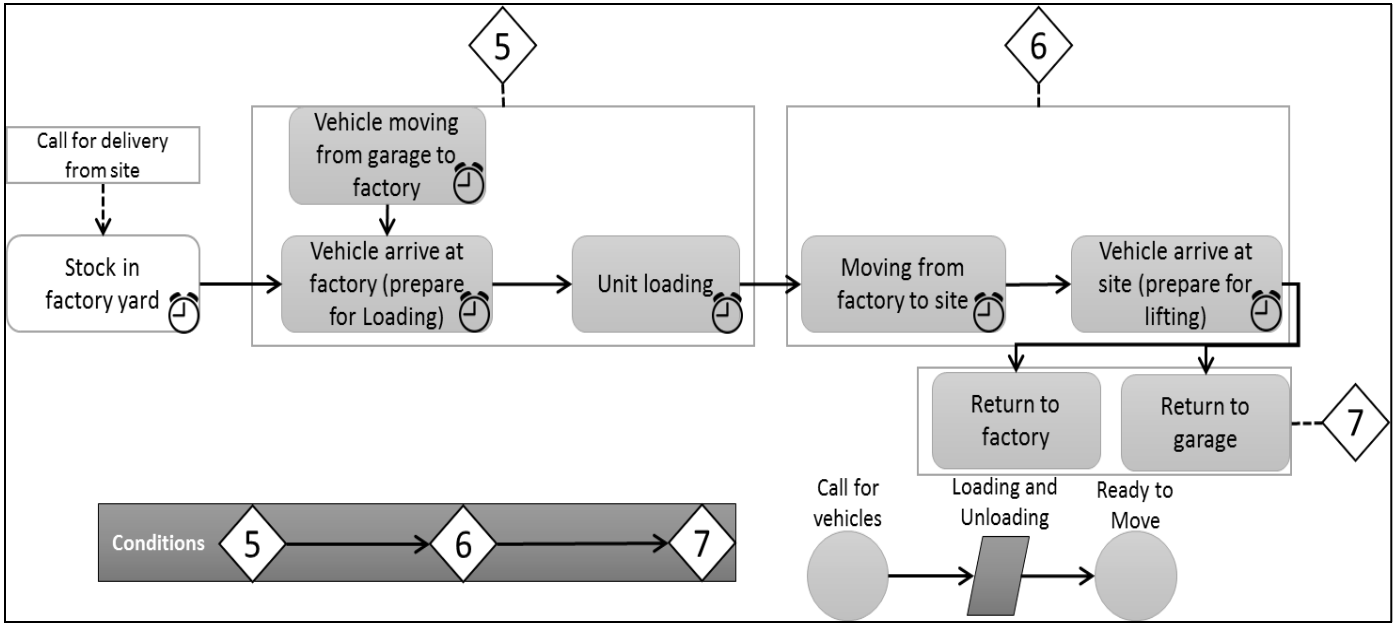


Figure 3-7. Conceptual Work Activity Groups in Transportation

4) On-site Installation

Modular construction on-site installation work process consists of none steps;foundation work, anchor construction, on-site delivery(lifting), module 1st floor assemble, module stacking, installation of a corridor plate, top floor installation, exterior joint construction, and completion. (Figure 3-8).

Node 8 represents the setting the foundation work duration (Figure 3-9). The modular building construction project, foundation work duration calculation is not different from the conventional construction method. In general, to calculate the foundation work duration, it is necessary to set the total work quantity, the heavy machine workability, and labor work capacity. In this model, however, work duration setting of these detailed activities is not different from conventional construction, so they are classified into a single work activity.

Node 9 represents the crane lifting work and installation works. The crane lifts work activities' working pattern are also not different from convention construction work activities; lift, swing, unload, and return. To determine the working duration, this simulation model provides a triangular distribution and constant duration functions. The installation work activity's working time should gradually decrease as the number of modular unit installation increases, resulting in a learning effect. However, the learning effect is not meaningful due to the connection error of between modular units, so that the general installation work duration applied in this simulation model.

Figure 3-8. Modular unit On-site Construction Work Process Example

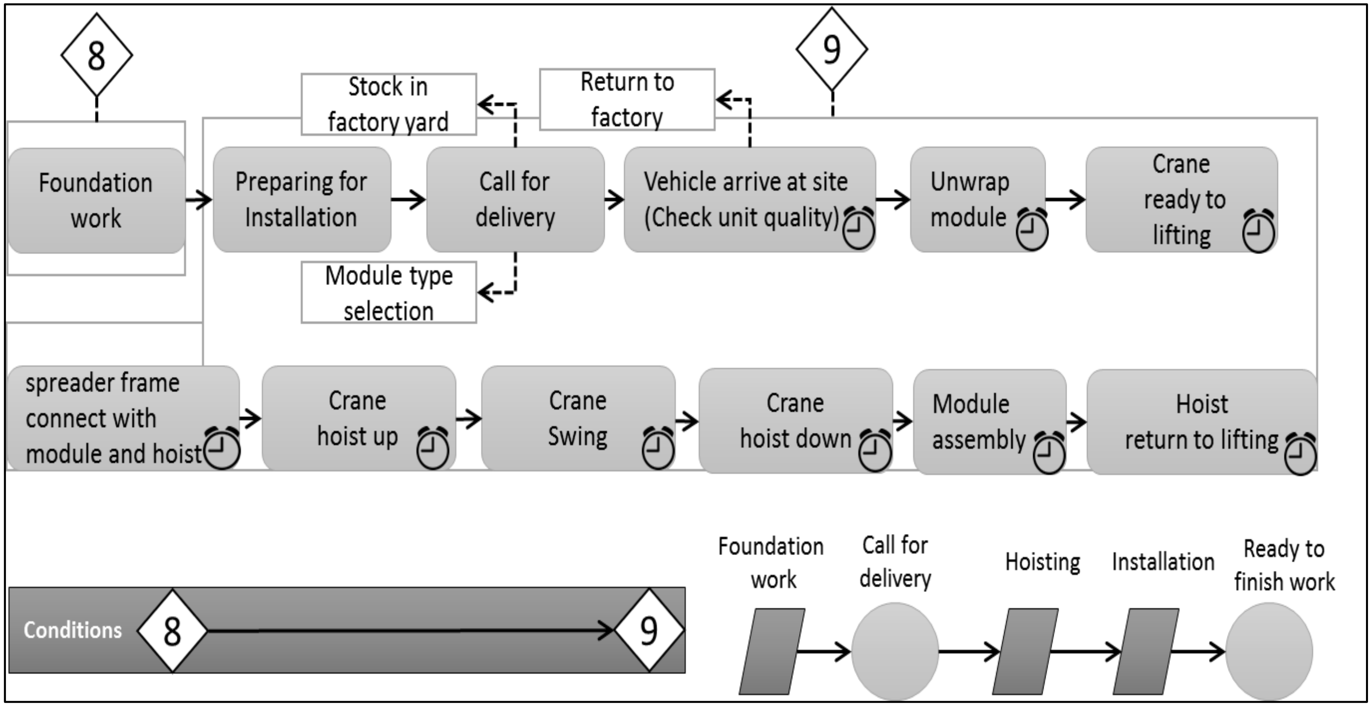


Figure 3-9. Conceptual Work Activity Groups in On-site Installation

3.2.3 Phase 3 – Developing DES based Modular Building Project Construction Operations Model

To realize work activities in the CYCLONE simulation model, QUEUE, Combi, and Function nodes are mainly used as described in Table 6. First node, the queue, represents the total number of required modular units and ready to work condition. The characteristics of CYCLONE element's relationship, there exist several Dummy elements in the model. The "Dummy" element does not play any role in the simulation, but is represented only for the connection of the preceding element.

1) Pre-work for Production Model: The first work, in this model, is steel structure and floor assemblies. The structure assembly work needs two main resources: worker and steel structure. As described in above, modular unit's main structural work is not performed main production line, but outside the factory (Figure 3-10).

In general, this work represents in conventional construction the steel structure erection work and its working duration is defined by workability and steel resource availability. Floor assembly work also needs two main resources: floor material and worker. In particular, floor structure of volumetric modular unit is mainly made of steel members and concrete. Therefore, the working time is longer than the steel structure working time because it requires time to make a floor structure and time required for curing.

After these works finished, the work of combining the steel structure and floor structure is carried out. At this time, since there is a difference in the work time between the steel and the floor structures, a work delay occurs for a certain period of time. This simulation model uses “Wait to work for SF Assemble” QUEUE node. When the entire work base is completed, the modular unit will move through the forklift to the main production line.

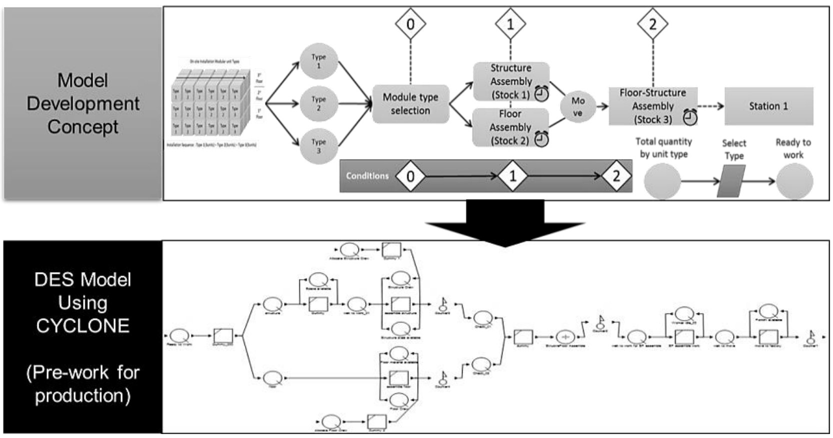


Figure 3-10. Pre-work for Production Simulation Model Development

2) Production Model: As shown in Figure 3-11, production work simulation model involves working at each workstation part and stock-in factory part. Each workstation has their work crews and work activities for making a modular unit. In continuous work production process, each workstation has several specific work activities, which are given same work and break times. In this paper, the specific work time and work characteristics of the detailed work for each station are not modeled. The purpose of this study is not to optimize the work distribution of each workstation, but to check whether it is effective to distribute the work time and break time equal to the overall scheduling. According to this, the main production simulation model consists of work duration of each station and work crew elements.

After the pre-work for production work, modular unit moves to the first station of the main production line. If station 1 work is not finished, modular unit is not moving. In addition, if the preceding work of workstation 1 has not been completed, the modular unit does not move to workstation 1 and waits until the predecessor work is finished. From the perspective of Lean construction, this waiting is waste time in overall schedule and has to remove. In general, however, modular building construction project manager does not consider this wasted time not as serious as the delay of other operations. Because the manager thought that this wasted time is a very small part of the overall scheduling because it does not take a few minutes each time. After the simulation model is developed, this research will examine how this wasted delay affects the overall scheduling and will discuss it.

After the last workstation work is complete, modular unit moves in stock area in a factory for waiting transportation. In this model, the maximum stock level setting is not allowed because the QUEUE element only provides initial length (initial quantity) and waiting position. To overcome this problem, this research uses the combination of QUEUE and Combi elements. For example, if “Stock in Factory” QUEUE node exceed the planned maximum capacity of stocks, the “Counter2” control the limit

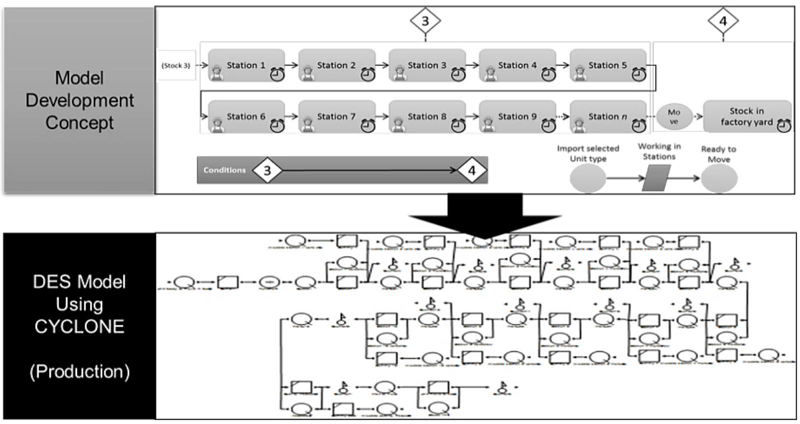


Figure 3-11. Production Simulation Model Development

3) Transportation Model: In transportation simulation model, there were two assumptions implemented in CYCLONE elements. First, initial length(total number of vehicles) is not limited during the simulation execution (Figure 3-12). Generally, the project manager calculates the total number of vehicles based on the total quantity of modular units. If this value is set as the initial value of the simulation model, the number of vehicles will not be freely fluctuated due to delays in transportation, production delays, and on-site installation delays. Therefore, in this model, the total number of initial required vehicles is set to more vehicles than existing calculation method, and the total number of necessary vehicles is calculated by the simulation result.

Second, distance values have been converted into the overall transportation time, and set as the initial input value. This conversion is not performed automatically within the model. Above all, the project manager enters the time required according to the basic transportation distance identified through the Google map, and sets the transportation time, according to the range of the triangular distribution function value to be used in this transportation simulation model.

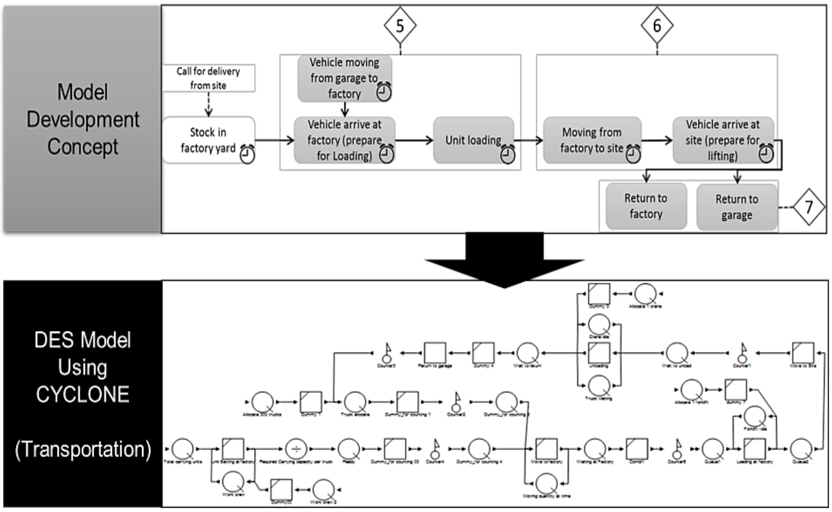


Figure 3-12. Transportation Simulation Model Development

4) On-site Installation Model: In on-site installation simulation model, two assumptions were implemented in CYCLONE element (Figure 3-13). First, the crane lifting time is set a time range with a triangular distribution function relative to the average lifting time. In order to reflect the accurate amount of time to the model, it is necessary to set all the time of the peak time according to the height change of the floor unit. However, the CYCLONE model does not continuously reflect the time setting according to the height change condition. Therefore, in the model inputs the lifting time range, the average lifting time of the tallest building unit such that the maximum likelihood in triangular distribution function.

Second, this on-site installation simulation model only includes where the volumetric modular unit is connected in the construction field. In general, the on-site installation work of modular construction represents not only connect of the module, but also the internal/external finishing work. This finishing work operations are carried out either while the modular unit is being installed or after all the modular units have been installed. Therefore, to reflect the general situation of the on-site installation simulation model, the work on finishing work is not reflected in the simulation model.

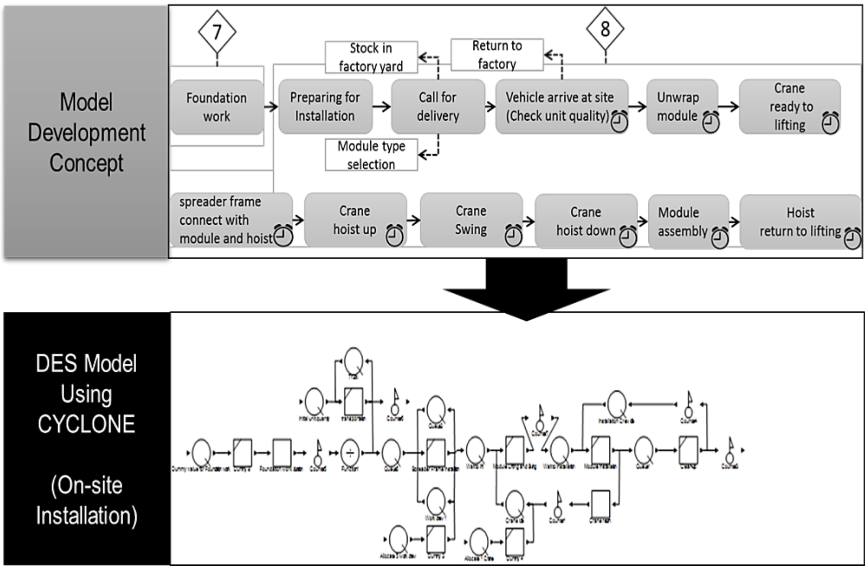


Figure 3-13. On-site Installation Simulation Model Development

3.2.4 Phase 4 – Model Tests for Verifying Development Model

From above sections, it can be summarized the basics necessary for the implementation of volumetric modular building construction project. Based on this information, a conceptual simulation model using CYCLONE is shown in from Figure 32 to Figure 35. These models have four main simulation modules; manufacturing, foundation, transportation, and on-site installation.

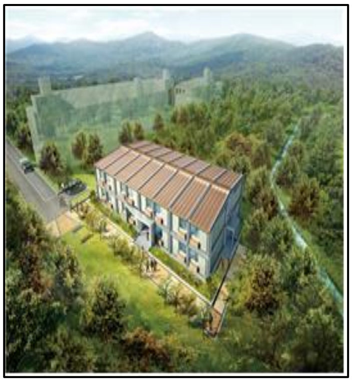
First, the manufacturing simulation module consists of several elements of the total number of units, manufacturing work duration, and workstations working limitations elements. These elements will be divided into several work activities in the detailed manufacturing simulation module.

Second, the foundation simulation module consists of total quantity of foundation work, foundation work duration, and foundation work resource limit elements. Unlike other simulation modules, this simulation module will be composed of simple work activities. In general, in order to carry out the foundation work in the conventional construction work, a lot of work and resources are needed and it is necessary to reflect it in the model. The modular construction is not much different from the conventional construction, but the main focus of in this study's simulation model is to determine how a typical level of work schedule is linked to the factory production schedule and how the work delay affects the overall schedule. Third, the transportation simulation module consists of the total number of truck, truck limit, and transportation time elements. These elements values will be set based on basic project information. Forth, the on-site installation simulation module has a crane lifting and assembly work elements. These two main elements have resource constraints and variance of working duration based on specific project information.

In addition, to evaluate this model's scheduling capability, actual modular building construction project information (Barracks dormitory project, 2013, Korea) is applied to simulate both structure working time and floor working time (Table 3-1). This project is one of the projects in eight different regions and is the last project. The reason for choosing this project was that it was the most suitable for reviewing model verification and entering actual data because it had the least project interference compared to other projects.

This project data will be used to review the validity of this model as well as the pre-work for production, production, transportation, and on-site installation models and described the data at each phase.

Table 3-1. Test Project Description

Project Overview	Description
	Project name: Dormitory
	Owner: Korean Army (Defense Installations Agency)
	Project scale: 3 stories
	Required total unit quantity : 80 units
	Structure type: Volumetric Modular units
	Total construction duration - Manufacturing : 2013.09.25 ~ 2013.10.03 - On-Site Foundation: 2013.09.01 ~ 2013. 10.03 Installation: 2013.10.20~2013.10.30

1) Pre-work for Production Simulation Model Tests

By using the input values in Table 3-2, the simulation results of the average pre-work for production schedule show similarities compared to their actual working time. As a result, the model of this study simulates the results of 6.5 days of the total structure assembly duration and 41.08 days of total floor assemble duration, and these simulation results are similar to the actual planned durations (Table 3-3). This means that this simulation model can be seen to be able to derive results that reflect the scheduling intent of the actual project schedule for pre-work for production phase (Figure 3-14).

Table 3-2. Input Variables and Values for Testing a Pre-work for Production Simulation Model Based on Actual Project Results

Input variables	Value
Initial structure quantities	80 units
Initial floor quantities	80 units
Structure assembles Duration(/unit)	120 minutes/unit
Floor Assemble duration(/unit)	80 minutes + 2 days(For curing) = 2960 minutes/unit
SF Assemble duration(/unit)	10 minutes/unit

Move to factory duration(/unit)	10 minutes/unit
Worker Idle value	(All) 4 workers/each work idle
Fork lift available	1 forklift available

Table 3-3. Test Results of Pre-work for Production Simulation Model

Contents	Actual Data	Simulation results (Runcount : 300)	
		Time output	Variance
Total structure Assemble duration	6 days	9447 minutes (6.5 days)	0.090
Total floor Assemble duration	40 days	59166 minutes (41.08 days)	0.874
Total pre-work for Production duration	42 days	59186 minutes (41.10 days)	0.896

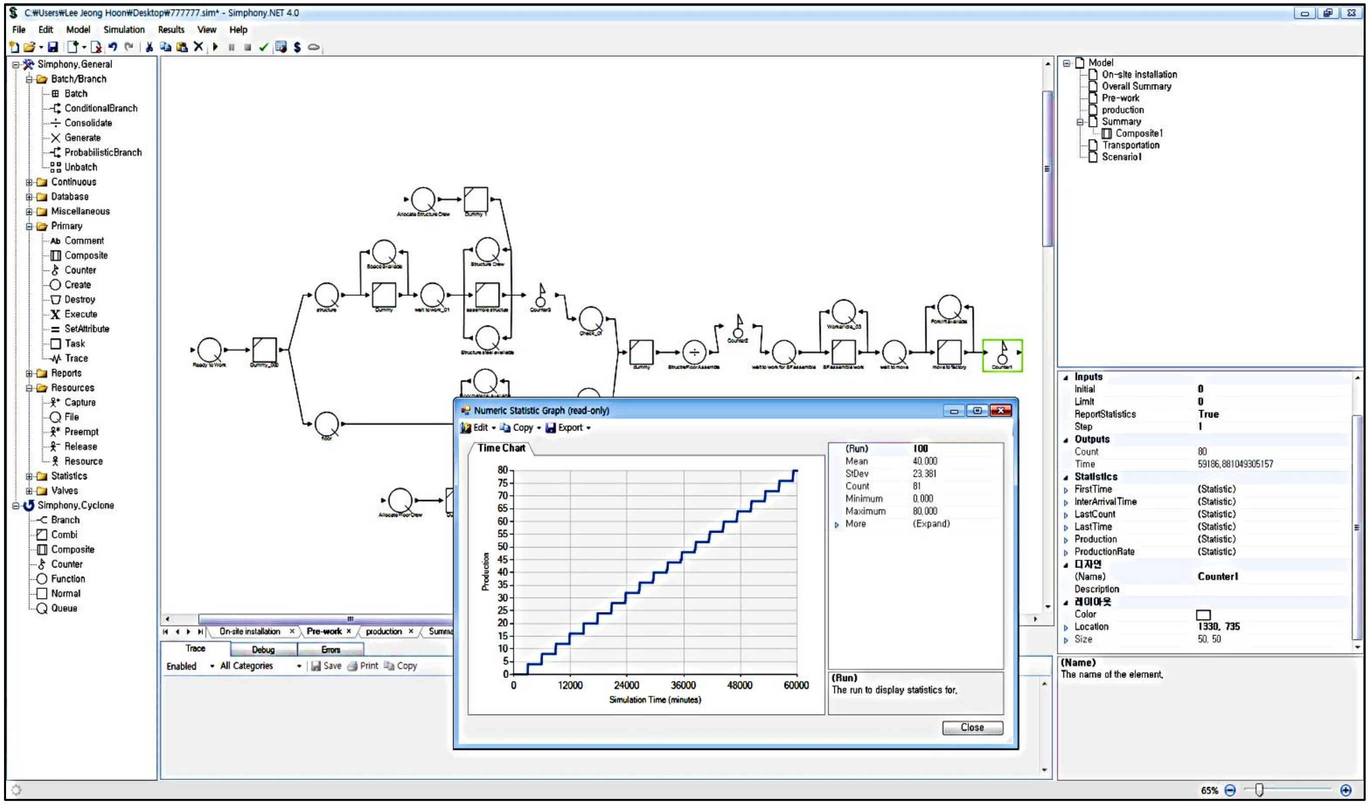


Figure 3-14. Pre-work for Production Simulation Model Result

2) Production Simulation Model Tests

To test the adequacy of the production simulation model, use the actual project data used in pre-work for production and main input variables are described in Table 3-4. This project was planned to be nine days to produce all 80 modular units, which means that at least 9 modular units must be produced each day. In addition, the total number of workstations is 10, and all workstations work for 50 minutes and have 10 minutes break.

Table 3-4. Input Variables and Values for Testing a Production Simulation Model

Input variables	Value
Total number of units	80 units
Total number of Workstations	10 workstations
Working time	50 minutes
Break time	10 minutes
Stock capability	100 units

By using the input values in Table 3-4, the simulation results of the production results show similarities compared to their actual operations data (Table 3-5).

As a result, the model of this study simulates the results of 9.3 days of total production duration and 0.0178 productivity rates. These simulation results are similar to the actual results. This means that this simulation model is able to derive results that reflect the scheduling intent of the actual project schedule for the production phase (Figure 3-15).

Table 3-5. Results of Production Simulation Model

Contents	Actual Data	Simulation results (Run : 300)	
		Time output	Variance
Total production Duration	9 days	9.3 days	0.001
Productivity (Total cycle/Total time)	0.0185	0.0178	0.003

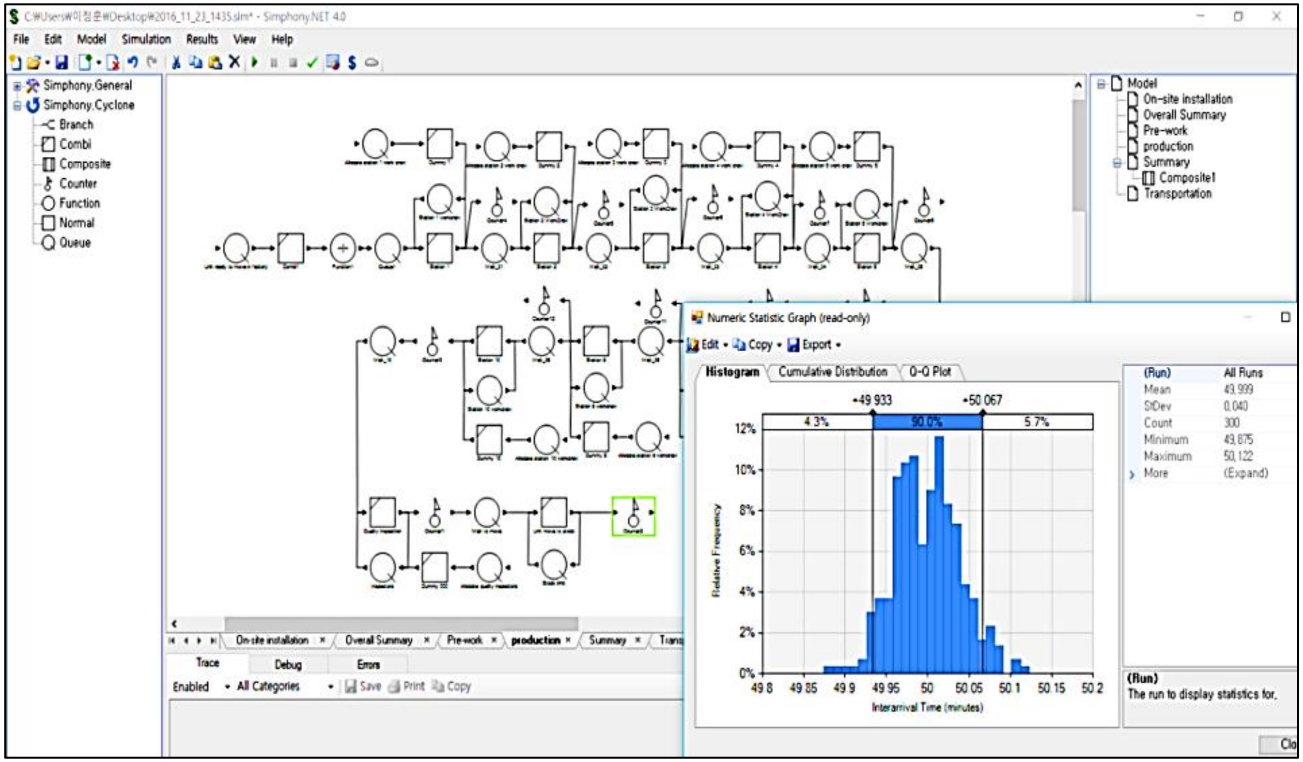


Figure 3-15. Production Simulation Model Results

3) Transportation Simulation Model Tests

To test the adequacy of the transportation simulation model, use the actual project data used in pre-work for a production (Table 3-6). As above mentioned, distance values were converted into time value and initial truck quantities were not defined.

Table 3-6. Input Variables and Values for Testing a Transportation Simulation Model

Input variables	Value
Total carrying quantity	80 units
Carrying capacity per vehicle	1 unit/vehicle
Number of vehicles waiting at the factory	2 vehicles
Number of vehicles waiting at the construction site	1 vehicles
Transportation time from garage to factory	100km converted into transportation time based on maximum vehicle speed (100km/80km/h =1.3 hours)

Transportation time from factory to site	330km converted into transportation time based on maximum vehicle speed (330km/60km/h = 5.5 hours)

By using the input values in Table 3-6, the simulation results of the average transportation results show similarities compared to their actual working times (Table 3-7). In actual projects, project manager assumed that the truck's factory returns were not considered at the beginning of the project.

According to this, the total number of required trucks resulting from the simulation is equal to the total number of units (Figure 3-16). The model of this study simulates the results of 8.17 days of total required transportation duration and 89.90 minutes of average vehicle arrive time from factory to on-site, and these simulation results are similar to the actual durations. This means that this simulation model can be seen to be able to derive results that reflect the scheduling intent of the actual project schedule for transportation phase

Table 3-7. Results of Transportation Simulation Model

Contents	Actual Data	Simulation results (Run: 300)	
		Time output Or Quantity	Variance
Total required number of vehicles	80 trucks	80 trucks	-
Total required transportation duration	8 days (Total installation duration – 2 days)	8.17 days	0.004

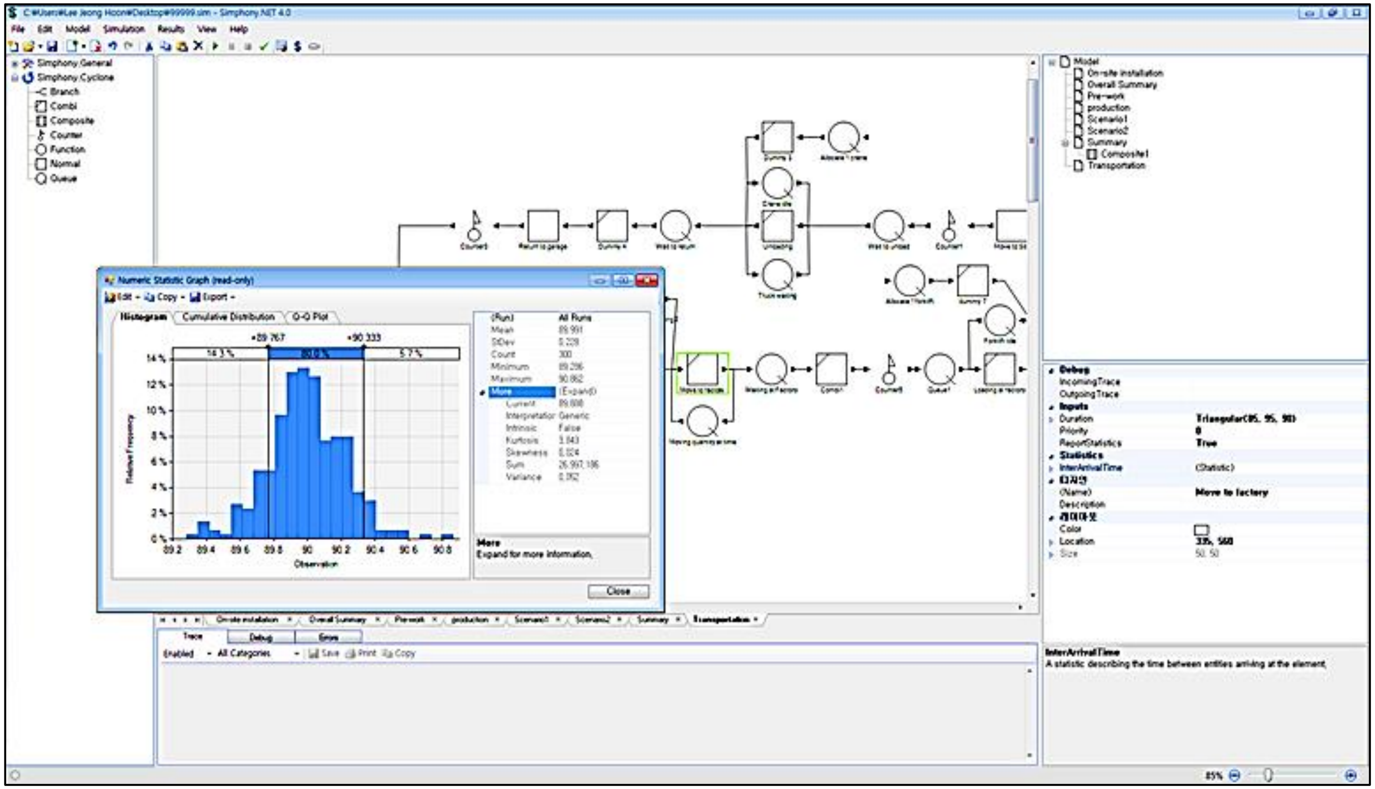


Figure 3-16. Transportation Simulation Test Results Example

4) On-site Installation Simulation Model Tests

To test the adequacy of the on-site installation simulation model, use the actual project data used in pre-work for production and main input variables are described in Table 3-8. As above mentioned, detailed crane lifting time calculation requirements and finishing work activities' characteristics is not reflected in this model.

Table 3-8. Input Values for Testing the On-site Installation Simulation Model

Contents	Values
Total number of modular units	80 units
Minimum waiting number of trucks at site	1 truck
Number of Crane	1 mobile truck crane
Expected crane lifting and swing time	15minutes/unit
Expected installation work time	10 minutes/unit

Table 3-9. Results of On-site Simulation Model

Contents	Actual Data	Simulation results (Run: 300)	
		Time output	Variance
Total foundation work duration	32 days	31.2 days	-
Total modular unit installation ration	10 days	10.39 days	0.003

By using the input values in Table 3-8, the simulation results of the average on-site installation results show similarities compared to the actual working durations (Table 3-9). In actual projects, project manager assumed that there is no installation conflict between modular unit crane lifting work and modular unit connection by workers during the overall on-site installation work. In addition, this project has no delay effect between the two schedules because the foundation schedule and manufacturing schedule are completely separated.

According to this, the total foundation work duration resulting from the simulation is similar to the actual foundation work duration. The model of this study simulates the results of 31.2 days of total foundation work duration and 10.39 days of total installation work duration, and these simulation results are similar to the actual durations (Figure 3-17). This means that this simulation model can be seen to be able to derive results that reflect the scheduling intent of the actual project schedule for on-site installation phase.

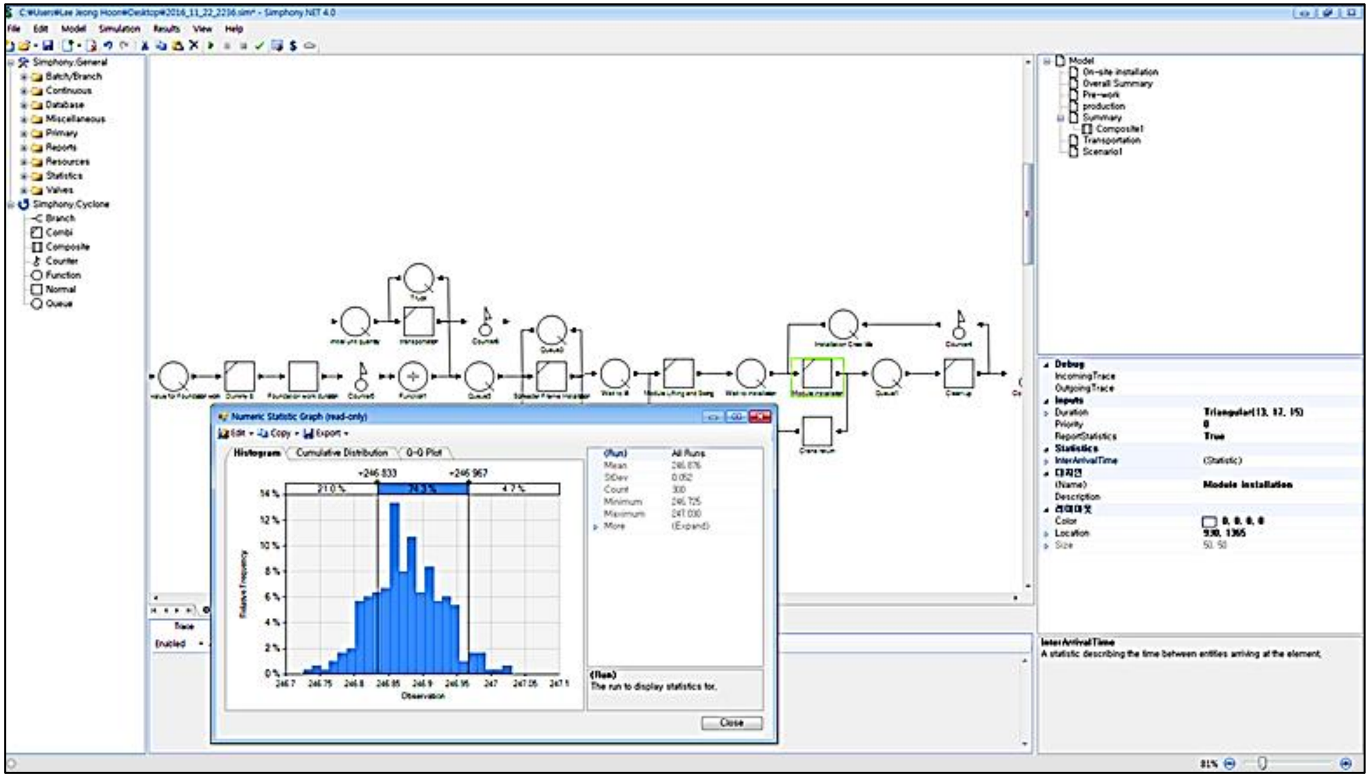


Figure 3-17. On-site Installation Simulation Model Results

3.2.5 Phase 5 – Integrate Four Simulation Models To Develop Overall Construction Operations Optimization Model

To implement the overall modular building construction project for schedule optimization, it requires work for integrating developed simulation models which means developing the construction process model. As described in Phase 3, the CYCLONE simulation tool is basically modeled as an activity-oriented method. This means that entities that represent one independent simulation model are difficult to allow other entities to be simulated concurrently. Therefore, additional work is needed to combine the four different simulation models developed previously. For example, a production simulation model entity represents a modular unit and a transportation simulation model entity represent a vehicle (truck), so these two different entities have to make the same level of the entity and not duplicate each other during the simulation execution. To do this, Halpin (1992) introduced four steps for developing process models (Table 3-10).

1) Flow unit identification: As a first step, the modeler must identify the system resource flow units that are relevant to system performance and for which transit time information is available or obtain from the field. The selection of the flow entities is very

important, since it indicates the degree of modeling detail incorporated into the operational model.

2) Development of flow unit cycles: Following identification of the flow units that appear relevant to the process being modeled, the next step in model formulation is to identify the full range of possible states that can be associated with each flow unit and to develop the cycle through which each flow unit passes.
3) Integration of Flow Unit Cycles: The flow unit cycles provide the elemental building components of the model. The structure and scope of the model are obtained by the integration and synthesis of the flow unit cycles.
4) Flow Unit Initialization: In order to analyze the model and determine the response of the system model, the various flow units involved must be initialized, in both number and initial location.

Based on four steps, this research defined and implemented specific requirements for integrating four different simulation models by one simulation model (Figure 3-18 and Figure 3-19).

Table 3-10. Four Different CYCLONE Model Integration Definition

Requirements	Definition and Implementation for integrating simulation models
Flow unit identification	1)Pre-work for production phase: Structure and Floor 2)Production phase: Modular unit 3)Transportation phase: Truck 4)On-site installation phase: Modular unit, Crane, and labor
Development of flow unit cycles	1)Pre-work for production phase ,Production phase, and On-site Installation: Based on total required unit quantities 2)Transportation phase: Based on factory and on-site requirements
Integration of flow unit cycles	Defined the total flow unit cycles based on total modular unit quantities

Flow unit initialization	1)Modular unit: Initializing at FUNCTION node of Pre-work for production 2)Worker and Equipment: Initializing at each QUEUE node 3)Truck: Initializing at the first of Transportation QUEUE node.

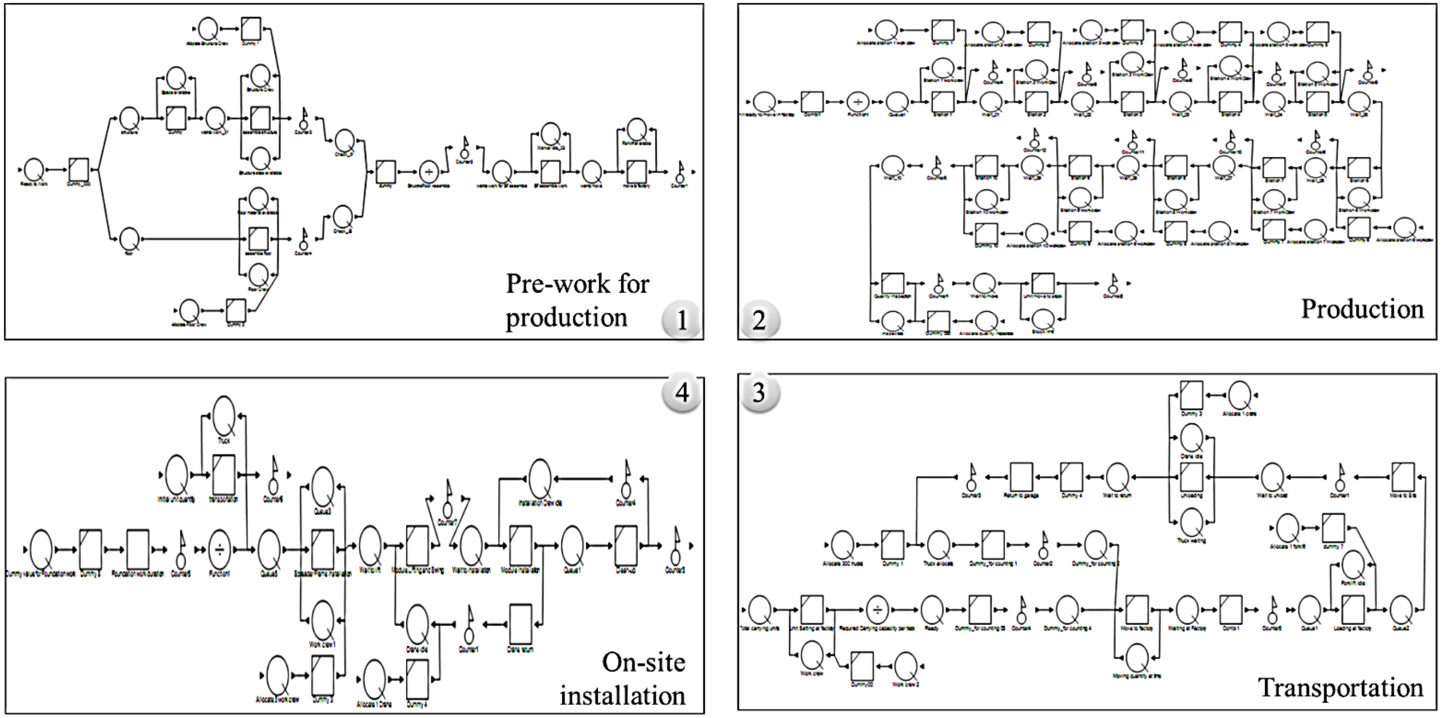


Figure 3-18. Four Different DES Models for Modular Building Construction Project

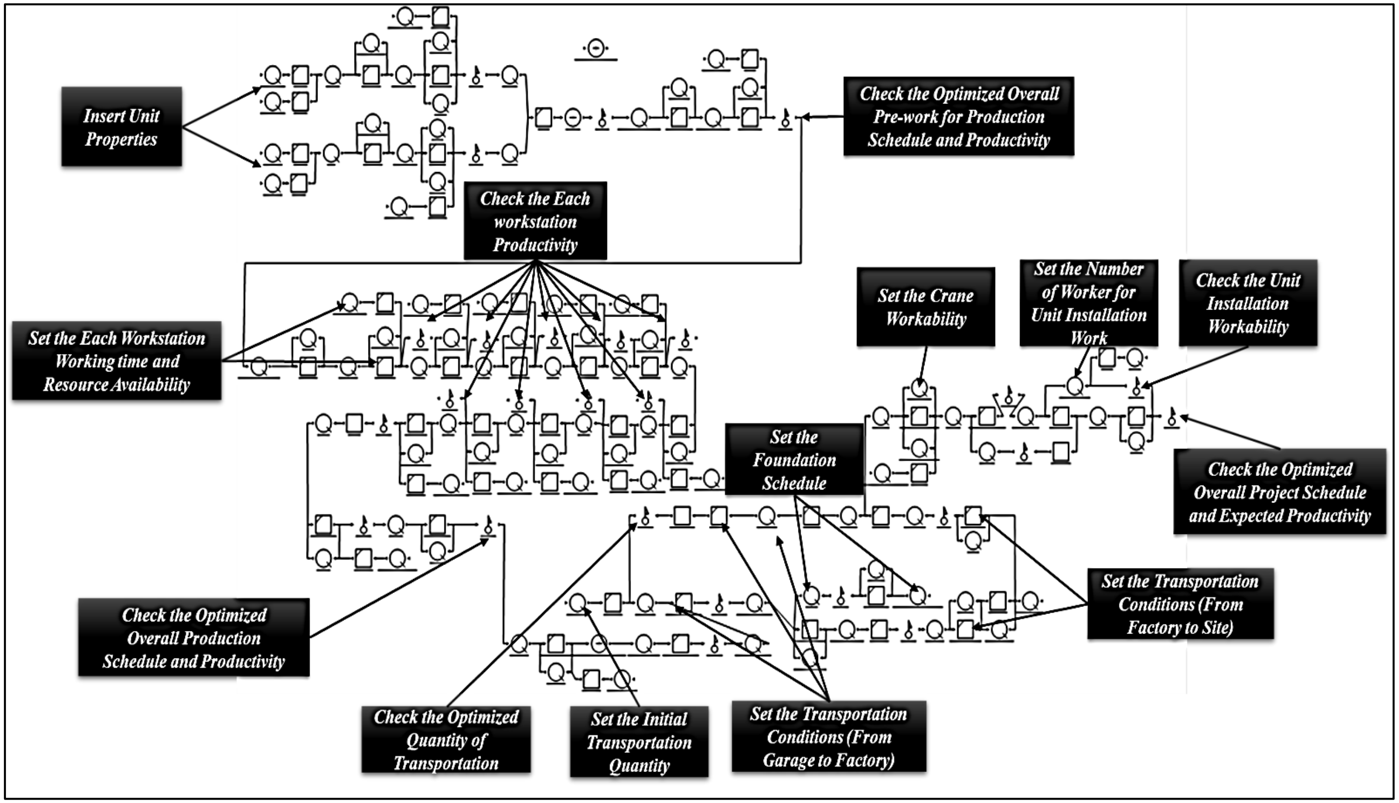


Figure 3-19. Modular Building Construction Simulation Model Integration Result

3.3 Summary

This chapter performed that development of modular building construction project resource and schedule optimizing simulation models based on CYCLONE. This research investigated comparison of conventional and modular constructions resources and schedule optimizations. Following the comparison results, this research proposed the detailed strategies for developing a modular building construction project resources and schedule optimizing simulation models following the pre-work for production phase, production phase, transportation phase, and on-site installation phase. After then, organizing the five model development phases.

1) Define the work activities at each phase
2) Developing a conceptual model based on work relationships
3) Developing DES based modular building construction schedule Optimization model
4) Model tests for verifying development model
5) Integrate four simulation models to develop overall schedule Optimization model

Each phase represents the main structure of modular building construction project schedule optimization simulation model development.

The optimization models made by CYCLONE simulation, which is activity-oriented simulation elements and each model contains work activity elements and resource utilization elements. Within this, this research performed the simulation model verification by each phase based on real modular building construction project information. After then, the developed models were converted into the process-oriented simulation model for optimizing the overall modular building construction schedule.

Chapter 4. Case Study

This chapter applied simulation model application to actual modular building construction project's planning and control problems and performed the sensitivity analysis based on requirements of resource and schedule optimizations. This research presents how the project manager can use the simulation results in scheduling.

4.1 Project Introduction

In general, project planning is performed as sequentially according to the work precedence or a combination of partially calculated schedules. For example, the general schedule of modular construction works is to make a production schedule, and then to set the total number of vehicles and on-site installation work duration. This sequence is the similar as obtaining the four different simulation models developed in this study. Therefore, according to the above process, the project manager fist derives the schedule for each step based on the four different simulation models presented in this study to build a modular building construction project schedule. After that, the project manager can get the overall project schedule from production to on-site installation by combining the four results. However, as described at the beginning of the research, this approach is difficult to determine how the influence of the schedule delay or the schedule shortening that occurs in each work stage affects the overall schedule of the project. Therefore, to validate the effectiveness of the proposed DES model and to improve the scheduling capability for project manager, three project cases were implemented that were performed by two different manufacturing companies (Figure 4-1).

Case 1 was performed based on single small scale project in 2012, Korea. This project was the first multi-story residential buildings made by volumetric units in Korea. Unfortunately, there is not perfectly matched case 2 (single large scale project) conditions' project within the acceptable range of release of the project information. According to this, case 2 and case 3 were performed based on military barracks project in 2012, Korea (Table 4-1 and Table 4-2). To protect the project information, some of the basic information (locations, detailed quantities, and site accessibilities) about Case 2 and Case 3 projects have been modified and applied (Table 4-3).

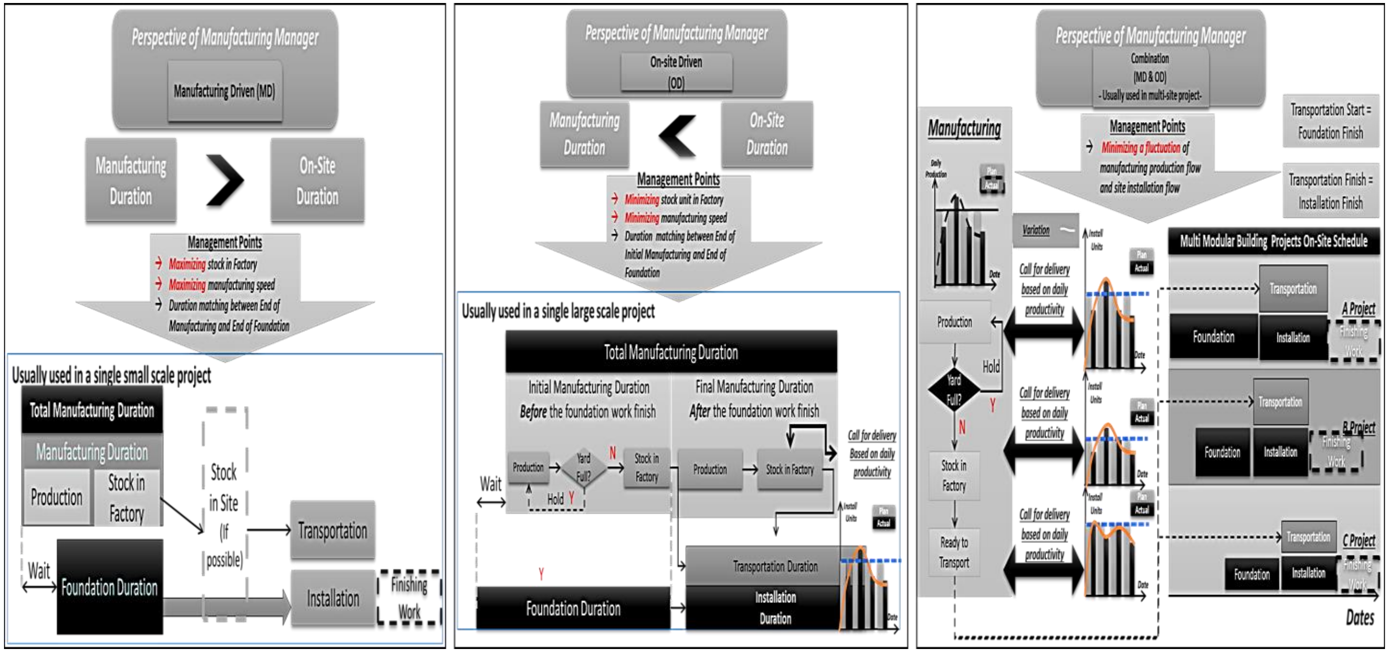


Figure 4-1. Project Case Types Applied to the Simulation Model

Table 4-1. Case 1 Project Descriptions

Target Project View and Types of units	Section	Contents
	Title of the project	Accommodations for Foreign Staff
	Client	POSCO
	Architect	POSCO A&C
	Location	16-15, Chang-dam dong, Kangnam-Gu, Seoul, Korea
	Site	376.30 m²
	Building Type	Accommodations
	Structure	Steel frame construction (Modular construction)
	Number of stories	3 Stories
	Modular unit Quantity	3x6m 18EA
	Total construction duration	31 days (including manufacturing, foundation, transportation, and on-site installation)

Table 4-2. Case 2 and Case 3 Projects Descriptions

Target Project View and Types of units	Section	Contents
	Title of the project	‘12 Military Barracks (Modular Construction)
	Duration	2013. 06. 24 ~ 2013. 12. 21.
	Total Cost	27.31 Billion dollars (Exclude VAT)
	Client	Defense Intelligence Agency
	Architect	Haenglim Architecture & Engineering CO.
	Location	Seoul Gwanak-gu Namhyun-dong 663 and 12 sites
	Site	53,779.0 m²
	Principal use	Military facilities
	Structure	Steel frame construction (Modular construction)
	Number of stories	1~3 Stories (Maximum height : 13.2M)
	Modular unit Quantity	Type A: 445 EA Type B: 550 EA / Total 995 EA

Table 4-3 Case 2 and Case 3 Total Required Units and Distance from Factory to Site

Site	Total Modular Unit Quantity and Distance from Factory to Site	
Site K	24 units (275km)	
Site L	32 units (273km)	
Site A	26 units (40km)	
Site E-1	120 units (183km)	
Site E-2		
Site D	48 units (288km)	Case 3 Project
Site G	22 units (290km)	
Site H	96 units (265km)	
Site M	168 units (160km)	
Site J	80 units (330km)	Case 2 Project
Site I	159 units (183km)	
Site F	58 units (260km)	
Site C	60 units (167km)	
Site B	96 units (62km)	
Total	989 units	

4.2 Sensitivity Analysis Using Case 1 Project

4.2.1 Case 1 Project Scheduling Problems

Case 1 project was first multi-story building made by volumetric modular unit structure in Korea. The company had experience in several construction projects using volumetric modular units, and most of these projects were temporary housing facilities and schools. The most important thing for this company when scheduling the Case 1 project, it was securing the on-site work durations (Figure 4-2).

The factory scheduling was enough to finish the total modular unit production because there were totally only 18 total modular units. However, this project was limited to the use of heavy equipment for lifting the modular units because the project was located in highly residential area. In addition, all internal and external finishing works were planned to be performed after the on-site installation work. Accordingly, the project manager, who has charged with manufacturing and on-site construction work, focused on the scheduling for the internal and external finishing working duration securing strategy rather than modular unit production schedule and on-site installation schedule.

This scheduling approach is logically problematic due to the characteristics of the project. However, as noted earlier, this project is located in a highly residential area, so the time to enter the modular unit is limited, which also affects the total daily working time. Therefore, it is necessary to modular construction scheduling that reflects the limited factor of the on-site installation work time even if the existing experience value is applied to the factory production schedule.

Figure 4-2. Case 1 Project On-Site Installation and Internal Finishing Work Examples

4.2.2 Simulation Results

To validate the optimal effect of this simulation model, it is necessary to compare the actual project execution period, the initial planned project execution period, and the project execution period derived from the simulation result.

The simulation results, based on this project information, should not exceed the total required construction duration (31 days) including manufacturing, transportation, and on-site installation works (Table 4-4).

Following the project information, the foundation work duration cannot affect the overall construction project schedule because it was expected to be shorter than the total modular unit manufacturing duration. Accordingly, the foundation work duration is not calculated in this model.

If four different simulation models are well integrated into one, the total number of units (18 units), the work time by each workstation(2hours), and the distance from factory to on-site (105km converted into 2 hours), the simulation results also close to 31 days.

Table 4-4. Case 1 Project Information and Constraints

Contents	Values
Total number of Modular units	18 units
Total Number of Workstations	10 workstations
Number of Forklift	2 Forklift
Distance from factory to On-site	105 km
Workstation working time	60min/station
Vehicle Speed	Under 60km/h
Maximum Stock quantity	Under 50 units
Number of On-site Installation Crane	1 truck crane (Lifting speed: under 1m/sec)

As shown in Figure 4-3, the total project duration was calculated to be 15334.85 minutes and it comes out to be 31 days (based on 8 hours a day working standard). As a result, this combined simulation model can be seen to be able to derive results that reflect the scheduling intent of the actual project manager for developing the overall manufacturing driven modular building construction schedule using volumetric modular units.

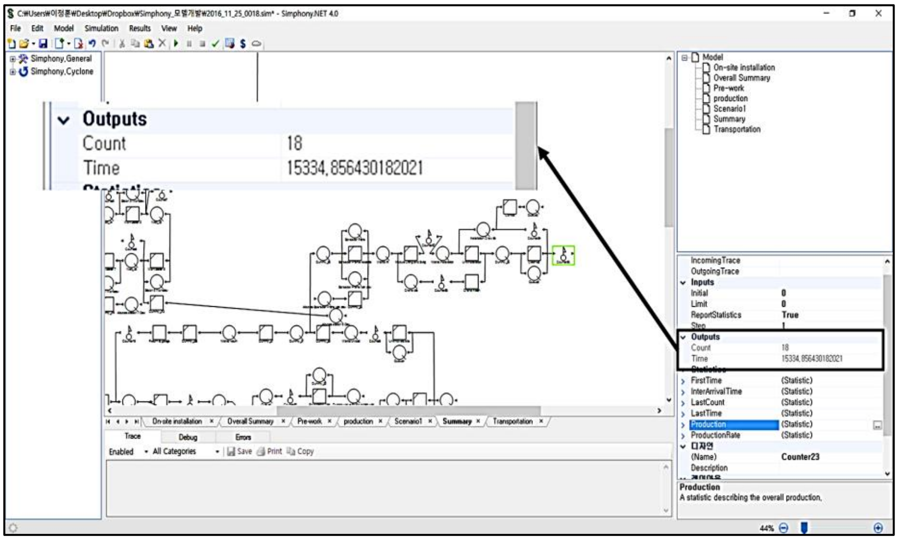


Figure 4-3. Simulation Result using Case 1 Project Information

After that, Case 1 project's main scheduling problems were applied in the simulation model. To do this, this model established two assumptions. First, manufactured modular unit leaves the factory as soon as it arrives at the factory stock area. As mentioned above, this project only required 18 modular units, so manufacturing duration also does not largely affect overall modular construction duration like as foundation work. However, the project has to calculate factory production time and on-site installation time to maximize the finishing work time. Therefore, it is necessary to find the optimal case that can maximize the finishing work time based on the change of factory production time and on-site installation time. Second, the modular unit lifting crane is only one available in on-site. In general, if reducing the on-site installation work time, it can increase the number of cranes used for on-site installation. However, this site is a highly residential area, so it is realistically impossible to increase the number of cranes.

Based on these two assumptions, simulation model 300 runs and its results shown in From Table 4-5 to Table 4-7. These results show that the available finishing work duration through the installation working hours and manufacturing working hours. The most significant result is that even if the on-site installation time is guaranteed to be at least 6 hours per day, there is not a large difference in the time available for finishing work even if the factory work time changes from 60minutes/station to 120minutes/station. In other words, if the project has 6 hours of on-site installation time, the fact that the factory is changed by 2 hours does not have a large impact on the overall schedule. These results also show that the on-site installation time can have a direct impact on on-site finishing work time if less than 6 hours available for on-site installation, regardless of manufacturing working times (Figure 4-4).

The main reason for this result that the total number of modules needed to be built was not as many as for affecting the schedule optimization result, so the time required for modules to move to the site and the time required to install the module in the on-site reducing the manufacturing working hours. Also, this simulation assumed not allowed the more lifting cane for modular unit on-site installation. This constraint is the main reason for decreasing finishing work duration due to delayed installation working time. Nevertheless, based on these results derived from giving the basic project information, the project manager should be able to run the project without having to shorten the factory production time to 60minutes/station, and also ensure a minimum on-site installation time of 6hours/day.

Table 4-5. Case 1 Simulation Results (60min/station)

Factory Condition	On-site conditions	
Workstation Working time	Available working time for crane lifting at on-site	Available working duration for finishing work at on-site
60min/station	8 hours/day	13152 minutes (27.4 days)
	7 hours/day	13008 minutes (27.1 days)
	6 hours/day	13012 minutes (27.1 days)
	5 hours/day	11712 minutes (24.4 days)
	4 hours/day	8880 minutes (18.5 days)

Table 4-6. Case 1 Simulation Results (90min/station)

Factory Condition	On-site conditions	
Workstation Working time	Available working time for crane lifting at on-site	Available working duration for finishing work at on-site
90min/station	8 hours/day	13248 minutes (27.6 days)
	7 hours/day	13296 minutes (27.7 days)
	6 hours/day	11212 minutes (23.4 days)
	5 hours/day	10371 minutes (21.6 days)
	4 hours/day	8898 minutes (18.5 days)

Table 4-7. Case 1 Simulation Results (120min/station)

Factory Condition	On-site conditions	
Workstation Working time	Available working time for crane lifting at on-site	Available working duration for finishing work at on-site
120min/station	8 hours/day	13101 minutes (27.3 days)
	7 hours/day	13058 minutes (27.2 days)
	6 hours/day	10941 minutes (22.8 days)
	5 hours/day	10267 minutes (21.3 days)
	4 hours/day	8638 minutes (17.9 days)

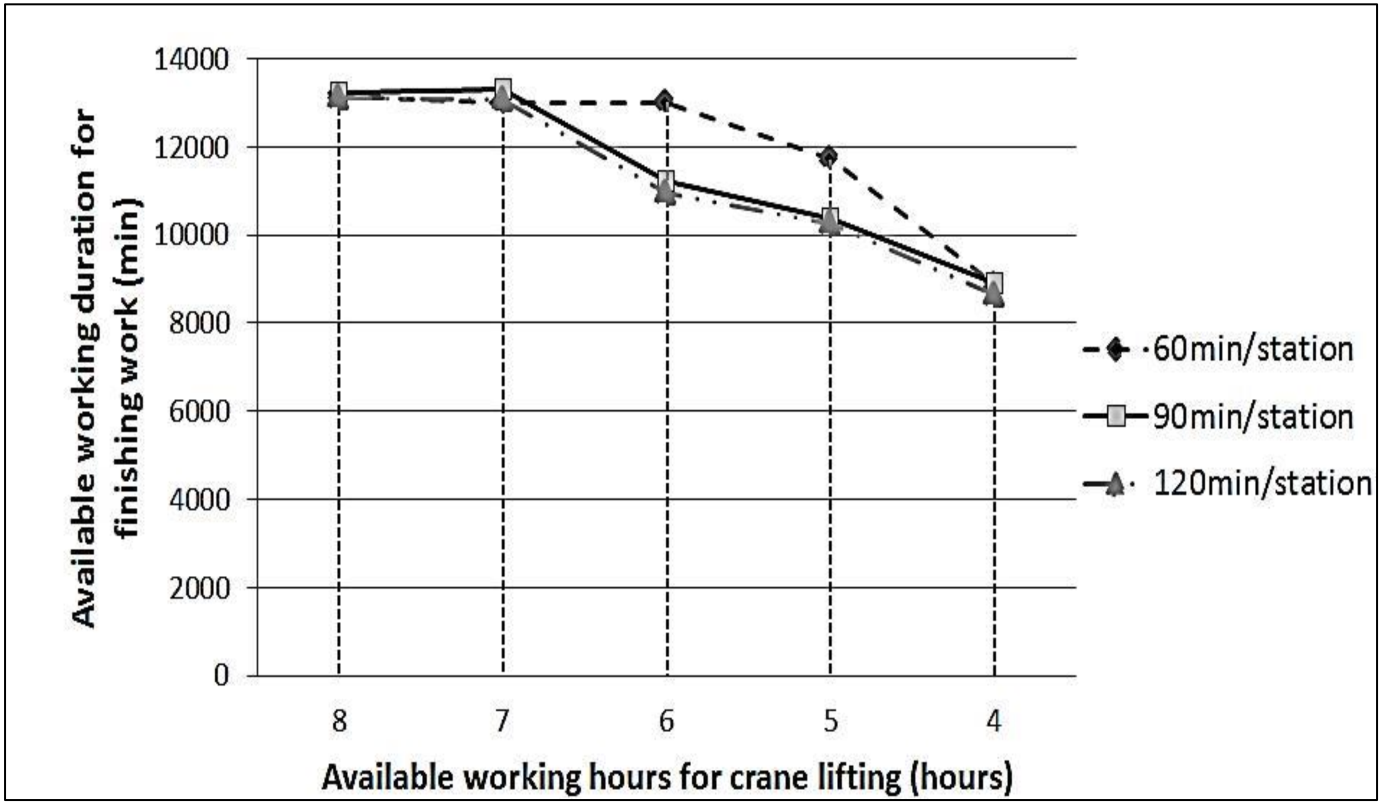


Figure 4-4. Overview of Case 1 Project Simulation Results

4.3 Sensitivity Analysis Using Case 2 and Case 3 Projects

4.3.1 Case 2 and Case 3 Projects Scheduling Problems

Case 2 and Case 3 projects were first multi-site modular building construction projects in Korea (Figure 4-5). As shown in Table 4-8, all the projects were carried out sequentially. For example, after all modular unit factory production for Site K were completed, the production of modular unit factory for Site L began.

On-site installation schedule, as well as factory production, is carried out sequentially for each project. When developing the overall project schedules, project manager was suffering from several constrains relating to production and transportation. First, the project manager had to decide the working time in each workstation at the production phase. In general, this company applied 50 minutes working time and 10 minutes break time during the production. Considering project scales, however, this working time was not enough to complete the project on time. Second, the floor of the modular unit was a reinforced concrete structure, so it required curing time. Precast Concrete (PC) slab structure could be used to shorten this time, but they did not use because of securing of quality of the floor and for preventing the construction error when assemble with main steel structure.

Third, the transportation time calculation was difficult because this project was a military facility, so it was not shown in transportation map such as Google Map or car navigation. Further, the transportation speed was limited under 60km/h because of preventing the modular unit's damage due to the wind and vehicle's road vibration. According to this, defined the detailed transportation time, from factory to on-site, and how much delays affect overall modular building construction project are difficult to confirm and detailed scheduling problems as follows.

1) The Case 2 project had to adjust the maximum number of stocks and the factory production time to on-site installation duration because the total unit production quantity exceeded the stock yard storage limit . Also, if the factory production time is determined to maximize the factory stock level, on-site installation work duration delays cause of overall scheduling fluctuations. To prevent this problem, the project manager should set the optimum overall working durations based on relationships between workstation working time variations and stock level variations.

2) The Case 3 project was scheduled to be completed at Site G factory production after Site D factory production (Table 4-9). As mentioned above, this project consists of 13 different construction

sites and its schedule goal is to minimize the overall construction duration to secure the following other construction project duration. In other words, the total construction duration required when the project was originally sequenced is 70 days for manufacturing, transportation, and on-site installation works. If the two projects are simultaneously run under the similar conditions of the Case 2 project, information on the effect of the construction duration shortening is needed. The most important information is whether it is possible to process at the current stock level and how much more space is needed if the current stock level is not enough to execute the project.

Figure 4-5. Case 2 and Case 3 Project Production and On-site Installation Examples

Table 4-8. Case 2 Project Information and Constraints

Contents	Values
Total Required Construction Duration	65 days
Total number of Modular units	80 units
Total Number of Workstations	10 workstations
Number of Forklift	2 Forklift
Distance from factory to On-site	330 km
Vehicle Speed	Under 60km/h
Maximum Stock quantity	45 units
Number of On-site Installation Crane	1 truck crane (Lifting speed: under 1m/sec)

Table 4-9. Case 3 Project Information and Constraints

Contents	Values
Total Required Construction Duration	Site D: 40 days (Except finishing work 15 days) Site G: 30 days (Except finishing work 10 days)
Total number of Modular units	Site D: 48 units Site G: 22 units
Total Number of Workstations	10 workstations
Number of Forklift	2 Forklift
Distance from factory to On-site	Site D: 288 km Site G: 290 km
Vehicle Speed	Under 60km/h
Maximum Stock quantity	45 units
Number of On-site Installation Crane	1 truck crane/site (Lifting speed: under 1m/sec)

4.3.2 Simulation Results

Following the project information, Case 2 and Case 3 project scheduling problems performed by the CYCLONE simulation models.

(1) Case 2 Project Simulation Results Analysis

As shown in from Table 4-10 to Table 4-12 represents the Case 2 project simulation results. The Case 2 project simulation purpose was that set the optimum overall working durations based on relationships between workstation working time variables and stock level variance through the developed CYCLONE simulation model.

Following the results, 60min/station working at a factory with 45 units stock limit case scheduling is most appropriate to perform the project execution. This result is intuitive without computer simulation. However, from the results of other cases, the project manager could execute the project in several different ways.

For example, in Table 4-11, 90min/station working condition with 45 stock level or 40 stock level cases results are similar as 60min/station working with 45 units stock level result. The main reason is that although the work time for each workstation has been slow, the supply of modular units has been smooth in the on-site installation with sufficient stock level. In addition, because the distance from the factory to site was long and the speed of the vehicle was limited, it was possible to off-site the time delayed by the production operation. Therefore, based on the results, the project manager could obtain some scheduling option information in Case 2 Project scheduling step, according to the basic project information, thereby enabling effective scheduling possible (Figure 4-6).

Table 4-10. Case 2 Project Simulation Results (60min/station)

Workstation Working time	Stock Level (Units)	Overall Construction Duration From manufacturing to On-site installation
60min/station	45	25436 minutes (52.9 days)
	40	25021 minutes (52.1 days)
	35	23984 minutes (49.9 days)
	30	23045 minutes (48.1 days)
	25	22994 minutes (47.9 days)

Table 4-11. Case 2 Project Simulation Results (90min/station)

Workstation Working time	Stock Level (Units)	Overall Construction Duration From Manufacturing to On-site installation
90min/station	45	24174 minutes (50.3 days)
	40	24014 minutes (50.0 days)
	35	23556 minutes (49.0 days)
	30	21324 minutes (44.4 days)
	25	20845 minutes (43.4 days)

Table 4-12. Case 2 Project Simulation Results (120min/station)

Workstation Working time	Stock Level (Units)	Overall Construction Duration From Manufacturing to On-site installation
120min/station	45	20957 minutes (43.7 days)
	40	19873 minutes (41.4 days)
	35	18754 minutes (39.0 days)
	30	16497 minutes (34.3 days)
	25	15974 minutes (33.2 days)

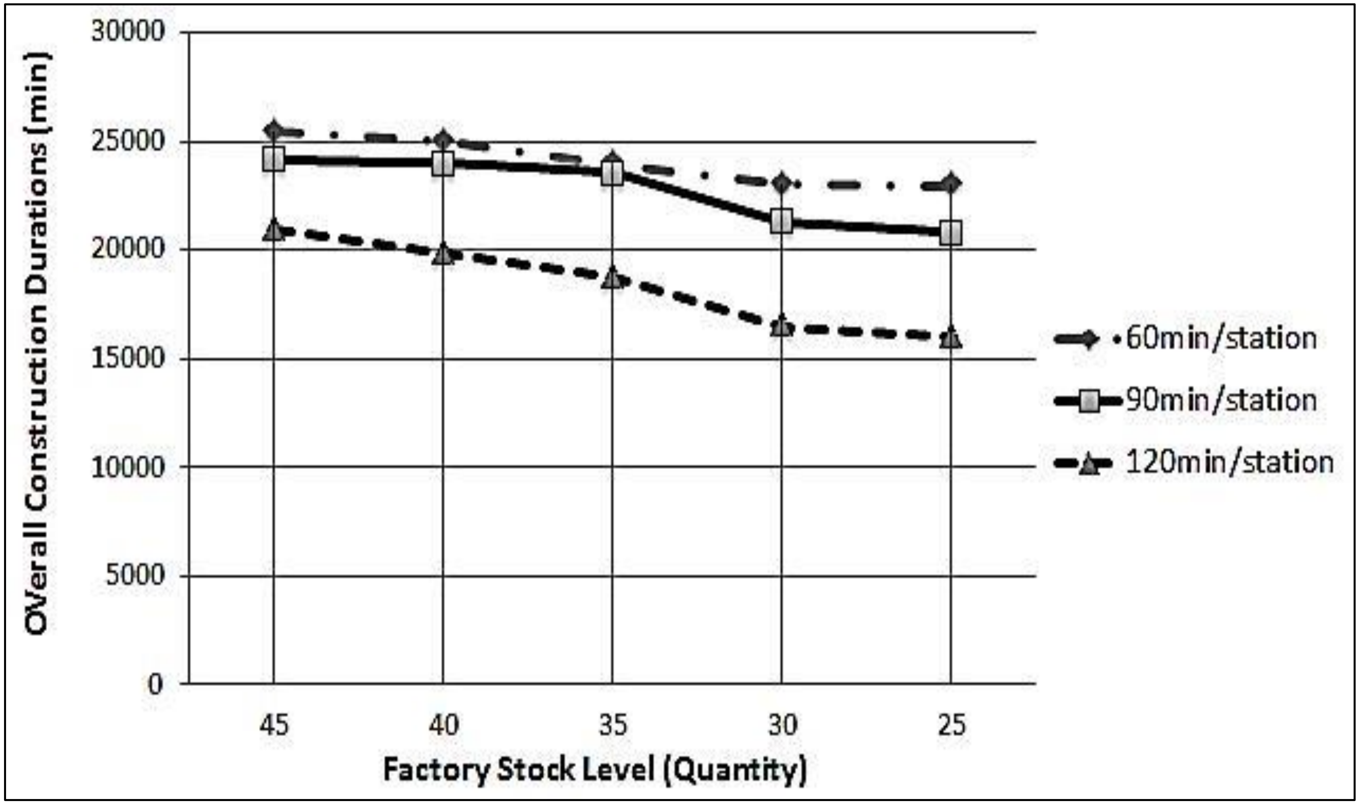


Figure 4-6. Overview of Case 2 Project Simulation Results

(2) Case 3 Project Simulation Results Analysis

The Case 3 project simulation purpose was that to minimize the overall construction duration to secure the following other construction project duration through the concurrent execution of two different construction site projects based on stock level variance. To simulate this condition, this research sets the assumptions for extracting the reliable result. First, the working time of workstation is assumed to be 60min/station and 90min/station for preventing effect of stock delay because 120min/station condition is not suitable for assuming this project conditions. Second, both sites assumed that the foundation work is completed at the same because these two project sizes are similar and use the same construction method.

According to this, this simulation starting point is same as finished the foundation work. Third, at the start of this simulation, this research assumed that 10 modular units have already been built in stock. Because, as mentioned earlier, these two projects are individually small, corresponding to the Case 1 project. This is because up to 10 modular units could already be built in during the foundation work duration.

Following the three assumptions and project basic information, the simulation results are shown in Table 4-13 and Table 4-14. Following the simulation results shown in Table 4-13, 60min/station working time condition and changing the stock level conditions was not satisfied with the project manager's required results. One of the main reasons is that the stock level, which connect both factory production speed and on-site installation speed, has not been sustained. Especially, after the stock level exceeded 55 units, it was confirmed that there was no difference in the overall schedule. This means that once the stock level exceeds 55 units, the stock level can no longer affect the overall scheduling. Same results as Table 4-13 and Table 4-14 show that there were not perfectly satisfied project manager's required results. However, despite the fact that factory production speed is slow, there were cases in which the simulation results are similar to those required by the project manager. This result is because, as mentioned above, the stock level value 55 units satisfied both the production speed and on-site installation conditions based on assumed conditions. Therefore, if the project manager wants to carry out both projects at the same time, it could be seen that after considering the assumptions of this research, additional stock space is needed to add about 10 modular units (Figure 4-7).

Table 4-13. Case 3 Project Simulation Results (60min/station)

Workstation Working time	Stock Level (Units)	Simulation Results (Run count: 300)	
		Site D Durations (Basic:40days)	Site G Durations (Basic:30days)
60min/station	40	25530 minutes (53.2 days)	20828 minutes (43.4 days)
	45	24210 minutes (50.4 days)	20019 minutes (41.7 days)
	50	22193 minutes (46.2 days)	19868 minutes (41.4 days)
	55	18945 minutes (39.4 days)	16584 minutes (34.5 days)
	60	18449 minutes (38.3 days)	15935 minutes (33.2 days)

Table 4-14. Case 3 Project Simulation results (90min/station)

Workstation Working time	Stock Level (Units)	Simulation Results (Run count: 300)	
		Site D Durations (Basic:40days)	Site G Durations (Basic: 30days)
90min/station	40	28458 minutes (59.3 days)	24304 minutes (50.6 days)
	45	25458 minutes (53.1 days)	21810 minutes (45.4 days)
	50	21042 minutes (43.8 days)	18568 minutes (38.7 days)
	55	19897 minutes (41.2 days)	16283 minutes (33.4 days)
	60	19736 minutes (41.1 days)	15638 minutes (32.4 days)

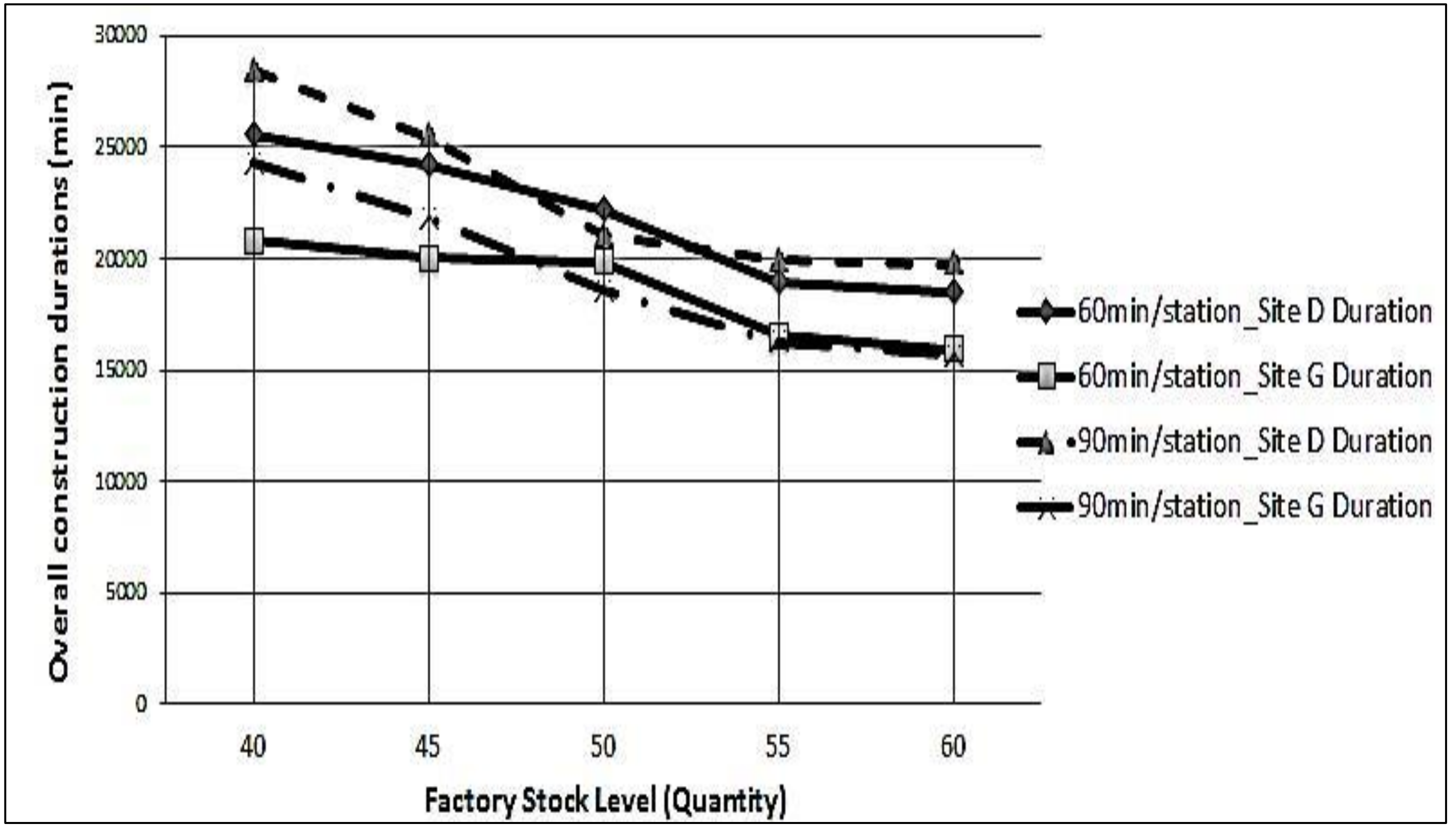


Figure 4-7. Overview of Case 3 Project Simulation Results

4.4 Summary

This chapter applied a schedule optimizing simulation model to the real modular building construction project scheduling problems for sensitivity analysis.

The first sensitivity analysis was done to provide maximum finishing work time at the on-site based on the change of factory production time and on-site installation time for project managers. As a result, simulation result shows that the project manager should be able to run the project without having to shorten the factory production time to 60minutes/station, and also ensure a minimum on-site installation time of 6hours/day.

The second sensitivity analysis has been done to provide stock level availabilities based on set the optimum overall working durations considering relationships between workstation working time variations and stock level variations for project managers. As a result, simulation results show two options identified to solve the scheduling problems based on initial project information. Before developing a schedule optimization model, this project scheduling problem solving method has been recognized as one. However, based on the results, the project manager can use the results to obtain various scheduling options information during the schedule development step.

The third sensitivity analysis was done to provide whether two different projects can be performed at the same time and how much inventory space more needed if the current stock level is not enough to execute the project. As a result, simulation result shows that if the project manager wants to carry out both projects at the same time, it could be seen that after considering the assumptions of this research, additional inventory space is needed to add about 10 modular units.

In conclusion, although the simulation results can vary following the project characteristics, these results show that how this schedule optimizing simulation model can contribute to use the overall modular building construction project schedule optimization in a real world. Additionally, the simulation results also use the productivity calculation and comparison following project constraints changes.

Chapter 5. Conclusions

This chapter summarizes the research results and this study's contribution to the technical and academic points of view is described. This research finally provides its limitations and required future works for enabling the research results to be applied to the real modular building construction projects in the future.

5.1 Research Results

Following the previous research results and overall construction market analysis, modular building construction is one of the ways of solving the lack of labor force, low productivity, schedule uncertainty, and environmental problems of conventional construction methods. The most different thing is that modular construction derived from manufacturing industry, which is possible to provide large amounts of modular units in shorten period. Therefore, it is recognized that the modular construction method is more effective than the conventional construction method in shortening the construction duration. However, due to the lack of understanding of the modular construction process of the project manager and the method of combining the construction schedule calculated by the type of work used in the conventional construction, the effect of reducing the construction schedule of the modular construction method is low.

To overcome these problems, the project manager needs to have an effective scheduling method considering the characteristics of stepwise operations of the modular construction process from the manufacturing to on-site installation based on the basic project information at the beginning of the planning and scheduling stages of the modular construction project.

To address these problems, this research suggested and developed the simulation model for optimizing the volumetric modular building construction project’s resources and project constraints to build a reasonable project planning and control strategies.

The results of this study have the following meaning. According to the results of the study, the specific stages of projects derived from the initial stage of a modular building construction affect the planning and control of the entire project. The case 2 and case 3 projects results show that the level of resource utilization and scheduling constraints of modular buildings does not increase sequentially by stages. In other words, the level of resource utilization and schedule delays in the on-site construction phase, which is the final stage in project planning and control, could be greater than the resource utilization level and schedule delay effects in the initial stage of factory production. Therefore, this simulation model is available for improving the project manager's understanding of overall modular building construction project process and providing the reliable scheduling results extraction.

5.2 Contributions

From a technical approach, this research used a discrete event simulation method to implement the repetitive working of the modular building construction project to enable project schedules from the modular project manager's perspective. In addition, the detailed work that composes the process from the factory production to the on-site installation is implemented in the simulation model and developed based on the CYCLON technical software which is widely used in the construction industry, so that it can be generally used in the modular building construction project using the volumetric modular unit. In addition, this research developed an independent simulation software for the volumetric modular unit used modular building construction project which reflects project scheduling constraints that are not implemented in the CYCLONE simulation model and improves the usability of the users. The developed simulation was verified based on the data of the modular construction project actually performed. In addition, when the basic project information is given, the research has been conducted on how the project manager could apply the scheduling problems and has encountered in the actual modular construction project scheduling stage to use this simulation model results.

From an academic point of view, this research shows that the scheduling of modular construction, which is one of the construction methods, requires concurrent scheduling rather than scheduling by the same as conventional construction scheduling methods. In various researches, they have been emphasized by research results using various computer simulation techniques that the method of combining the schedules made by individual work types is not effective. However, in modular construction, the scheduling criterion is different according to the stage of factory production, transportation, and on-site installation, and the place where the work is performed is completely isolated. Therefore, the scheduling ways of partial scheduling method has been used in modular construction project.

For these reasons, various scheduling researches of modular construction method focus on optimizing operations at specific stages, such as presenting factory production scheduling methods through optimizing of manufacturing worker batch arrangements, or optimizing on-site scheduling by optimizing on-site lifting cranes placement location. However, in order to these individuals developed optimization methods to be applied to actual projects and reflected in the scheduling results, there is a need for a schedule simulation in which the work flows smoothly at the points where these steps are connected as well as the work characteristics at each step.

In this research, the direction of development of simulation model based on the concepts of SCM and Lean construction, which can reflect the simultaneous scheduling of the overall project and the continuity of workflow, has been established. Based on this, this research developed a simulation model utilizing the computer simulation method. This has contributed to that the previous researches have partially overcome the limitations that were not fully applied to the overall project schedule optimizing simulation model by partially applying the concepts of SCM and Lean construction principle based to modular building construction project scheduling.

5.3 Future Research

Although it noted that this research performed based on limited research scope, additional research and examinations have to perform to further validate the suggested simulation model. Regarding this, three research suggests the future research area as follows.

1) This research does not reflect the scheduling for finishing work. In general, the finishing work can be performed after the modular unit is installed or after all the installation is completed. In order to make detailed scheduling of the overall project, this part needs to be studied in depth.

2) This research has developed a simulation model based on several theoretical knowledge of manufacturing industry and construction industry for modular building construction project using volumetric modular unit. Therefore, there is a limit to be applied to a project using a modular unit of other structure, such as an infill system or penalizing type system structure. However, if a project having these structures is modified to the factory production part of the simulation model presented in this study, it

can be fully utilized. In addition, CYCLONE, the simulation tool used in this study, does not reflect labor productivity and machine productivity to control the overall scheduling. Therefore, it is necessary to increase the reliability of modular construction scheduling based on the productivity-based simulation model widely used not only in the construction industry, but also in the manufacturing, plant, and automobile industries.

3) This research was performed simulation model validations for a modular building construction project in a specific nation. However, in order to extend the usability of the developed model, it is necessary to verify various projects according to the experience level of the modular building construction projects.

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國 文 抄 錄

離散事件分析 方法을 活用한 工業化 建築工事 計劃 및 制御 分析方案

모듈러 건축공법은 공장에서 전체 공종의 60~80%을 완료하고 이를 현장으로 운반하여 현장설치를 통해 목적물을 완성하는 것이다. 따라서 모듈러 건축공법의 가장 큰 특징 중 하나는 공장제작 기간 동안 현장 기초작업이 동시에 수행될 수 있기 때문에 기존 현장중심의 건축공사 방법에 비해 공사기간 단축이 용이하다는 것이다. 이에, 이 공법은 최근 건설업계가 겪고 있는 노동력 부족 및 낮은 생산성 문제를 해결하는 데 기여할 수 있어 점차 이에 대한 수요가 증가하고 있다.

그러나, 최근 조사된 모듈러 건축 프로젝트 현황 보고서에 따르면, 모듈러 건축 프로젝트는 공사비 절감 측면에서는 기존 건축공사에 비해 우수하지만 공사기간 측면에서 큰 차이를 보이지 못하고 있다. 그 이유 중 하나는 건축공사의 프로젝트 계획 및 관리 방법을 유지하면서, 모듈러 건축 프로젝트의 공장제작부터 현장설치까지에 이르는 자원활용 및 작업 특성을 동시에 고려한 계획 및 관리 기준 설정이 실제와 차이가 발생되기 때문이다.

이에 본 연구는 모듈러 건축 프로젝트 초기 단계에서 프로젝트

매니저에게 모듈러 건축 프로세스(공장제작, 운송, 현장설치)에 따른 작업특성 및 자원활용수준 변화에 따른 프로젝트 계획 및 관리 기준을 제공할 수 있는 시뮬레이션 모델을 개발하였다. 본 연구의 목적을 달성하기 위해 1) 모듈러 건축 계획 및 관리를 위해 필요한 구성요소를 정의하며, 2) 이를 바탕으로 이산사건 시뮬레이션 방법을 통해 모듈러 건축 계획 및 관리를 위한 시뮬레이션 모델을 개발하며, 3) 개발된 모델의 타당성 검토 및 검증을 위해 본 연구에서 정의 한 모듈러 건축 프로젝트 타입 별 특성에 적합한 실제 수행된 모듈러 건축 사례 적용을 수행하였다.

본 연구에서 제안하는 모듈러 건축 프로젝트 계획 및 관리 방안은 제작, 운송, 현장설치 단계별 작업특성 및 자원활용수준을 동시에 고려하여 프로젝트 제약조건 변화에 따른 적정 작업기간 산정 및 프로젝트 관리 기준선을 설정하는 프로젝트 매니저의 의사결정을 지원한다. 이는 프로젝트 계획단계의 자원 및 일정 관리 기준 산정 단계에서 기본적인 프로젝트 정보를 수치화 하여 시뮬레이션 모델에 입력하여 최종 산출된 결과값의 조합 및 평균을 바탕으로 이루어지기 때문에 다양한 프로젝트 수행계획을 수립하는 의사결정에 활용 가능하다. 또한, 프로젝트 수행단계에서 자원 및 일정 관리 시, 프로젝트 수행과정 중 발생되는 프로젝트 제약조건 또는 문제점을 현재 시점을 기준으로 이를 수치화 하여 향후 프로젝트 계획 및 관리 기준 변경 필요성을 판단하는데 기여할 수 있다.

주요어: 건설관리, 프로젝트 계획 및 관리, 모듈러 빌딩 건축, 스케쥴링, 자원 최적화, 이산사건 시뮬레이션

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