Master's Science in Engineering

Quantity Decision Support Model for Mid-to-high-rise Modular Construction Projects

by

Onekyu Choi

Department of Architecture & Architectural Engineering

The Graduate School

Seoul National University

February 2018

Quantity Decision Support Model for Mid-to-high-rise Modular Construction Projects

by

Onekyu Choi

A thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Engineering

Seoul National University

2017

Quantity Decision Support Model for Mid-to-high-rise Modular Construction Projects

지도교수 이 현 수

이 논문을 공학석사 학위논문으로 제출함

2017년 12월

서울대학교 대학원

건 축 학 과

최 원 규

최원규의 공학석사 학위논문을 인준함

2017年 12月

위 원 장 ________ 박 문 서 ________ (인)

부 위 원 장 ________ 이 현 수 ________ (인)

위 원 ________ 여 명 석 ________ (인)

Quantity Decision Support Model for Mid-to-high-rise Modular Construction Projects

December, 2017

Approved by Dissertation Committee:

Moonseo Park

Hyun-Soo Lee

MyoungSouk Yeo

Abstract

Quantity Decision Support Model for Mid-to-high-rise Modular Construction Projects

Onekyu Choi
Department of Architecture
The Graduate School
Seoul National University

Modular construction can improve construction quality and accuracy through manufacturing process, and it allows massive production and cost savings by repeatedly producing the same unit. In particular, it is possible to shorten the time because the on-site work and the manufacturing can be carried out at the same time. However, according to the modular construction project survey report, there is no significant difference in the average construction period of modular construction and conventional construction. This is due to schedule delay problems that occur in the progression on-site work. Therefore, it is necessary to select alternatives to prevent schedule delay during on-site construction progressing. Especially, in case of large-scale modular construction project, module assembly on site is performed simultaneously with manufacturing in factory. Identification of alternatives should be done at the same time, taking into account both the manufacturing and the on-site work. In this study, the management factors of large-scale modular construction project were identified through the IDEF0 modeling, and the factory production amount and the on-site construction amount management model was derived. This will reduce the schedule delay problem that occurs in the progression on-site work of a large scale modular construction.

Keyword : Modular construction, Decision-making, Change management, Construction Management

Student Number : 2016-21089

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Research Background

Modular construction which enables improvement of efficiency and standardization of quality control has emerged in order to solve the problem of productivity degradation in the construction industry(Alazzaz et al., 2014). Modular construction refers to a method of manufacturing 70~80% materials in a factory and lifting and assembling the materials after they are shipped to the on-site(Carlson, 1991; Kim et al., 2013). This method has been applied to various building types such as military barracks, schools, offices, and houses(Smith, 2010, Mullens, 2011; Lee et al., 2017) and has been developed in Korea since 2000(Cho et al., 2007).

Modular construction can improve construction quality and accuracy through manufacturing process, and it allows massive production and cost savings by repeatedly producing the same unit(Lawson et al., 2014). In particular, it is possible to shorten the time because the on-site work and the manufacturing can be carried out at the same time(Velamati, 2012; MBI, 2013).

However, according to the modular construction project survey report, modular construction does not show the time reduction effect(IPA, 2015).

This is due to transportation delays, errors in factory production, and construction duration delays occurred by difference between production amount in factory and required amount from on-site and erroneous order delivery during the construction(Thomas et al., 2000; Alvanchi et al., 2012, Shin et al. 2016). Thus, it is necessary to produce a process which assesses alternatives considering the problems occurred during the project(Pinto and Kharbanda, 1995; Ibbs et al., 2001; Qi Hao, 2008; Zhen et al., 2009). For example, if the on-site module workload is less than planned, alternatives would be to provide additional workforce to compensate for the construction duration or to extend the construction duration, and the alternative selection process should be proceeded through a systematic process.

However, currently there is no established process to solve problems that arise during the on-site construction of the modular construction project(Shin et al. 2016), and only the on-site alternatives are considered when selecting the alternatives for problem solving(Kang 2006). The selection process does not consider the factory production process, which accounts for 70-80% of the modular construction project process. In addition, since the factory produces most of the materials for the construction, the range of alternatives considering the on-site construction is reduced compared to the conventional construction(Na Lu et al., 2009). Therefore, considering only the on-site alternatives reduces the efficiency of alternative selection for problem solving during the on-site construction, which causes construction duration to increase.

Ultimately, The current alternative selection process is a reason for hindering the advantages of modular construction projects.

Modular construction projects can be classified into two cases according to their sizes. On the first case, the factory production process is limited to the on-site foundation period. As the amount of modules required is small, the case enables complete factory production of modules that are necessary for on-site installation at the time of on-site foundation work. Therefore, modules produced in factory are simply transported and assembled in on-site after the foundation work(Lee, 2017). On the other case, for the large-scale modular construction projects, the factory production process proceeds after the on-site foundation work due to the large amount of modules required for the site installation(Lee, 2017). Hence, in the case of small-scale modular construction, only the number of modules for the on-site is managed during lifting and assembling when management for not only the number of modules for the on-site but also the production amount in factory is necessitated for the large-scale modular construction. In addition, large-scale modular construction projects are more likely to take advantage of the modular construction than the small-scale modular construction since factory production and on-site work can be carried out simultaneously for a longer period of time.

In short, in the case of large-scale modular construction projects, since the factory production progresses simultaneously with lifting and assembling process during the on-site work(Lee, 2017), it is necessitated to consider both factory and on-site to identify the alternatives for solving problems of the construction phase. Also, as the project progresses, the number of remaining modules decreases. As a result, alternative comparison of the factory and on-site is required with the changed effectiveness of alternatives influencing on the factory and on-site, so the series of process, which is comparison and identifying the alternatives, must be conducted in the alternative selection process. For example, if the factory production process causes continuous rework at the site, it is effective to change the factory production process when the cause is found at the beginning of the module production, but after most of the modules have been already reworked and constructed, on-site reworking becomes more efficient alternative.

The purpose of this study is to develop a model that enables improved management of factory production and on-site construction quantities reflecting the properties of large-scale modular construction after deriving the different management factors of large-scale modular construction through process modeling. In modular construction, it is difficult to manage change(Lu 2009), and it is necessary to manage and change the module manufacturing volume and assembling in site by the influence of change management.

1.2. Research Objective and Scope

The objective of this research is developing quantity decision support model for mid-to-high rise modular construction projects during construction phase.

This research detailed objective is as follows.

1) Confirming how the factors influencing the delay of the modular project are related to the actual construction process.
2) Deriving the difference in management factors of large-scale modular construction
3) Reflecting the characteristics of large-scale modular construction, developing quantity management model.

In this study, the scope is limited to construction duration, the key management factor, during the simultaneous progression of lifting and assembling in the process of large-scale modular projects after the on-site foundation work in unit modular construction.

1.3. Research Procedure

The research procedure is as follows.

1) Identify change management, which is a problem-solving process during construction, through literature review. Also, search process modeling for acquiring properties of large-scale modular construction and derive the construction duration effect factors in the progression of modular construction for process modeling. 2) Identify difference of small-scale modular construction and large-scale modular construction during the construction through IDEF0 Modeling. 3) Develop a quantity of module management model that reflects the properties of large-scale modular construction. 4) Verify the effectiveness of the model through the actual case studies and execute decision-making which take factory and on-site into consideration simultaneously.

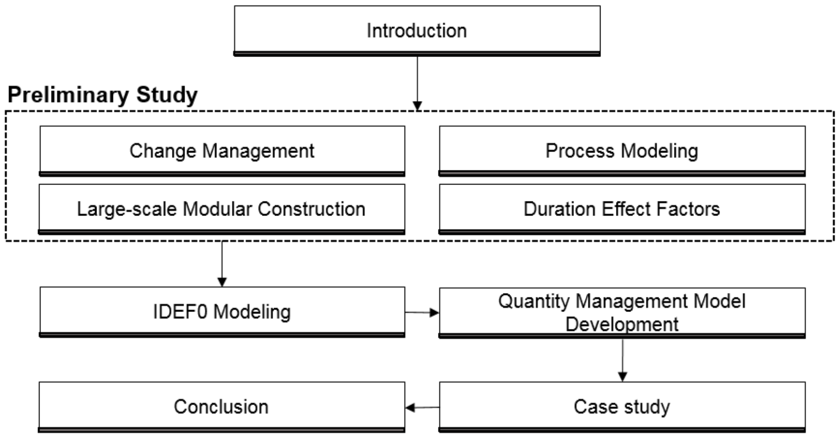

Fig. 1-1. Research Process

Chapter 2. Preliminary Study

In this chapter, contents of preliminary studies for a process of large-scale modular construction project, change management, and process modeling using IDEF0. In detail, derive the variables, effect factors, that affect on the construction duration delay for the process modeling.

2.1. Large–scale Modular Construction Projects

In the large-scale construction projects, factory starts production before the end of foundation work. The reason is that the foundation work duration also increases following the size of projects size, but when factory production starts at the same time as the foundation work, the factory production is stopped stops due to the lack of storage space. Thus, most of the factory production and on-site module assembly progress at the same time. Construction duration planning of A project in the US, which is a large-scale modular construction project, shows that factory production starts after the on-site foundation work and proceeds most of module lifting and assembly simultaneously at the site.

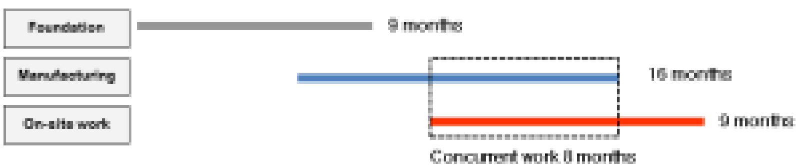

Fig. 2-1. Planning of large scale A modular construction project

Also, large-scale modular construction differs from small-scale modular construction by the repetitive cycles in on-site construction. In the case of small-scale modular construction, the modules, which are already completedly produced in factory, are transported to the site at the beginning of lifting and assembly, and only the process of transporation and on-site work are repeated at the site after the foundation work. Therefore, it is required to manage only the numbers of the modules to be constructed in the site. Since the number of required modules is small, the number of repetition cycles is small, and it is difficult to apply the changed alternatives to the factory production (Fig. 2).

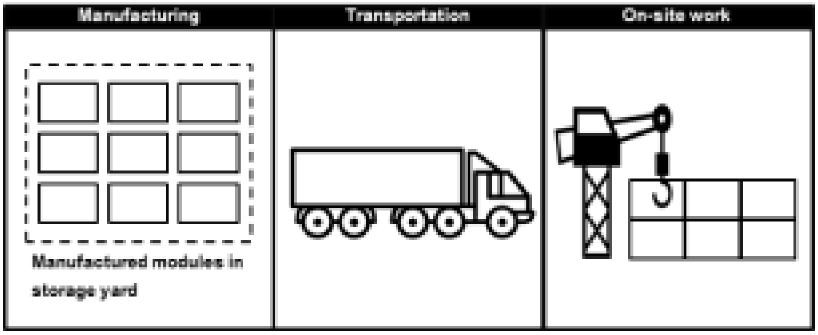

Fig 2-2. Small scale modular construction project cycle

in the progression on-site work

However, in the case of large-scale modular construction, the process, factory production – transportation – on-site work, is repeatedly performed during the on-site work because of simultaneous progression of factory production and on-site work. Therefore, it is necessary to manage not only the module construction volume in the site but the module production volume at the factory due to on-going factory production even during the progression of module lifting and assembly in the on-site construction. Also, the repetitive cycles of factory production – transportation – on-site work also increases because the number of modules required is relatively large. The process may increase the possibility of project delay during the construction due to transportation delay, errors in factory production, and inaccurate transportation order(Thomas at et al., 2000, Alvanchi et al., 2012). Especially the difference between the on-site work volume and factory production volume(Thomas at et al., 2000, Alvanchi et al., 2012) might lead to the delay in the large-scale modular proejct (Fig. 3).

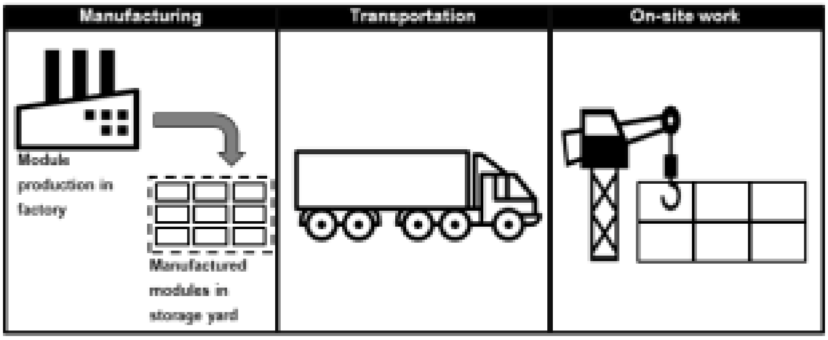

Fig 2-3. Large scale modular construction project cycle
in the progression on-site work

Recent research trends in modular construction focus on planning and factory production rather than solving the real problems during the actual construction (Shin et al., 2016). Lee et al. (2012) presented the main factors to review at the early stage of modular construction by organizing and analyzing the causes of the problems in each phase of modular construction through the experts' interviews. In Kim et al. (2013), it optimized the production process of domestic modular unit factories by eliminating the factors that lower the productivity in the factory production process using the DSM (Dependency Structure Matrix). Kim et al. (2015) derives the modular unit factory production order and transportation order by design the modular unit production process planning algorithm model that supports multiple projects. Shin et al. (2016) analyzed the case of advanced modular construction in the foreign countries and proposed domestic modular construction process. In short, recent research on modular construction has been focused on improvement of the productivity in planning and factory production process.

However, a modular construction, as a part of the construction project, is also completed on site, and problem-solving methods in the site affects the efficiency of the entire project. Thus, the research of problem-solving methods during the on-site modular construction is unavoidable. This study differs from the previous studies in that it presents a model that identify the construction duration delay problem which possibility occur in the progression of on-site work and uses the model to propose decision-making process considering the factory and the site at the same time.

2.2. Change Management

Changes arise frequently in Construction projects(Zhen et al., 2010). Throughout the entire projects, changes occur for various reasons, affecting time duration and costs(Qi Hao et al., 2008). Thus, decision makers need to be aware of the changes and cope with situation(Ibbs et al., 2001). The process of identifying, evaluating, and managing the changes occurred during the project execution phase is called change management(Qi Hao et al., 2009; Ko et al., 2009; Cho et al., 2014). If the changes are not resolved by the certified management process, the delays may occur continuously, accompanying with additional need for equipment, materials, and work(Qi Hao et al., 2008). Therefore, studies have been conducted to derive process models for change management(Ibbs et al., 2001; Charoenngam et al., 2003; Sun et al., 2006; Qi Hao et al., 2008; Ko et al., 2009, Zhen et al., 2010; Cho et al., 2014). Qi Ho et al. (2008) proposed a general change management process model as shown in Fig. 4.

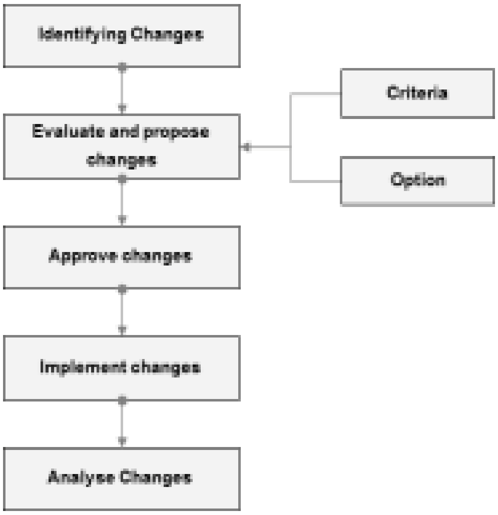

Fig. 2-4. General change process model

When problems occur, the change management process model follows the steps: recognize changed factors, evaluate and suggest changes, approve and enforce the changes, and analyze the applied changes. In evaluating changes and proposing alternatives, it is necessary to evaluate the effect on the time and cost of the accepted change based on the various criteria and options and select the best alternative by analysis of other alternative changes(Qi Hao et al. 2008). The process undergoes the decision-making process(Qi Hao et al. 2008).

Decision-making process of modular construction projects considers only the on-site alternatives when evaluating and proposing the alternatives(Kang 2006). For instance, even if continuous delay occurs in the site due to the factory production process, the problems are seek to resolved solely through the on-site rework. This alternative decision-making process does not consider the factory production process, which accounts for 70-80% of modular construction project processes. Therefore, since modular construction proceeds the factory production and on-site work simultaneously in different places, alternative making process should be dualized, consider both factory and the site, and choose the best alternative in order to shorten the construction duration. During the process, respective criteria is required to judge the construction duration delay and decision-making process.

2.3. Process Modeling

For alternative selection of change management in large-scale modular construction, it is required to analyze difference of the simultaneous process in factory production and on-site work between the large-scale modular construction and other existing construction. In business perspective, a process is defined as a set of actions that results from the one or more inputs(Hammer, 1993). Construction is basically a process-based industry, and it can achieve competitiveness through proper management and improvement of the construction process(Lee et al. 2002).

Process modeling is defined as representation all the activities related to the knowledge of the system into a process and integration the activities(Scholz-Reiter and Stickel, 1996). IDEF0, one of the process modeling methodologies, was developed to model the USFK weapons production process. IDEF0 is a functional modeling method that decomposes from the upper level step by step to show the process in more detail and identifies activities performed in the process(George M., 2001).

IDEF0 enables process management in functional and organizational aspects(George M., 2001), and with hierarchical and standarized structure, it is suitable for illustrate the process of construction industry(Kim et al., 2006). Due to the properties of large-scale modular construction which repeats the cycles, factory production – transportation – on-site work, modular construction business process modeling can be used to identify activities and factors affecting on the factory production and on-site construction through IDEF0. In particular, step-by-step segmentation allows identification the mutual effects of simultaneous process, which is the property of large-scale modular projects. IDEF0 modeling method is as follows.

Table 2-1. ICOM function

Factor	Explanation
Activity	The action that performs the function
Input	The factor is consumed as function is performed
Control	Constraints to control function
Output	The output produced as a result of a function or activity
Mechanism	Person or entity performing the function

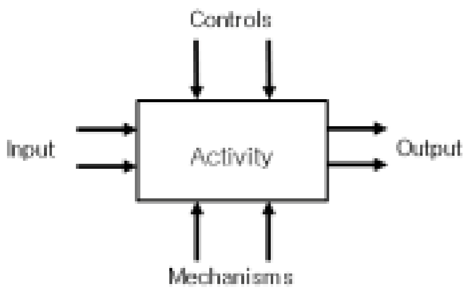

Fig. 2-5. IDEF0 notation

2.4. Construction Duration Effect Factors

To model the modular construction project process, the study derives the effect factors on the construction duration, the scope of the study as mentioned above. Following the process of modular construction, the construction duration effect factors are divided into three stages in modular construction. (Table 1) illustrates the effect factors which removed the redundant factors from the previous studies and are classified according to production, transportation, and on-site work.

The variables are the factors influencing on the modular construction duration. The variables are divided into two categories, variables to consider during the planning and effect variables during the construction process. The effect variables and variables to control are shown as follows(Table 2).

In other words, even the planning does not perfectly predict the variables due to uncertainties, and they affect the construction duration in construction process. Therefore, the variables need to be managed in order to prevent the delay of construction duration. ICOM Matrix, a preliminary process for IDEF0 process modeling, reflects the factors derived.

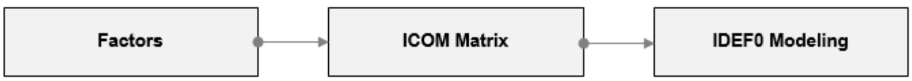

Fig. 2-6. Factors utilization

Table 2-2. Variables for modular construction duration

Classification	Variables	Reference
Manufacturing	Productivity of factory	Kim et al.(2015)
	A sequence of producing modular unit	
	Storage yard	
	Capacity of factory utilization	Mullens(2011)
	Workability	Hofman Erwin(2009
	Rework	Lee et al.(2012)
	Manufacturing process	Kim et al.(2013)
Transportation	Number of trailer	Kim et al.(2015)
	Transit time	
	Road condition	Ryan(2010)
	Traffic congestion	
	Delay	Lee et al.(2012)
	Rework	
	Weather	Shin et al.(2016)
	Sequence error	
On-site work	Sequence error	Kim et al.(2015)
	Modular unit type	
	Number of workers	
	Modular unit quantity	
	Crew workability	Hartman(2010)
	Rework	Lee et al.(2012)
	Construction Error	Lawson(2014)
	Weather	Shin et al.(2016)

Table 2-3. Variables during on-site construction progressing

Classification	Variables	Reference
Manufacturing	Size of Storage Yard	Kim et al.(2015)
	Crew Workability	Hofman Erwin(2009
	Rework	Lee et al.(2012)
	Manufacturing process	Kim et al.(2013)
Transportation	Road condition	Ryan(2010)
	Delay	Lee et al.(2012)
	Rework	
	Weather	Shin et al.(2016)
	Sequence error	
On-site work	Crew workability	Hartman(2010)
	Rework	Lee et al.(2012)
	Construction Error	Lawson(2014)
	Weather	Shin et al.(2016)

2.5. Summary

In this chapter, this research investigated the latest research trends of modular construction and definition of large - scale modular construction. In addition, change management, which is a problem solving process, was examined during construction phase, and duration effect factors for process modeling and process modeling were derived to characterize large - scale modular construction. In the case of change management, modular construction requires a different process than conventional construction.

Chapter 3. Quantity Model Development

In this chapter, the different management method between the small-scale modular construction and large-scale modular construction was derived through the process modeling using IDEF0. Also, it derives the formula that enables the calculation of expected number of manufacturing modules and assemble modules and suggests a management model using the formula.

Fig. 3-1. Quantity management model development process

3.1. Process Modeling Using IDEF0

The process modeling was performed after deriving ICOM Matrix based on construction duration effect factors derived above and the domestic modular construction projects.

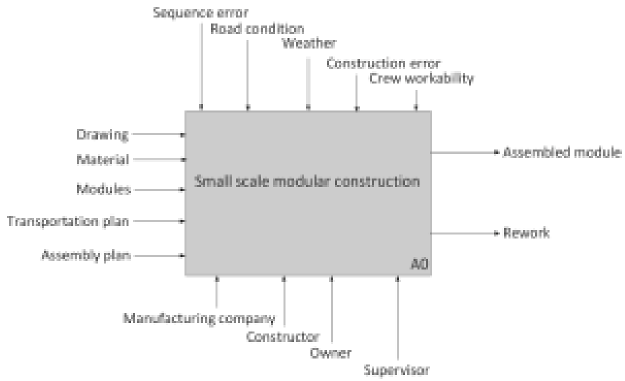

Fig. 3-2. IDEF0 level0 small scale modular construction

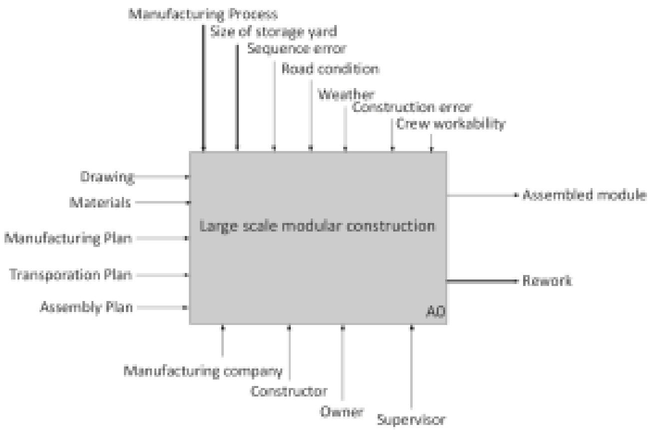

Fig. 3-3. IDEF0 level0 Large scale modular construction

A0 Level shows that both small-scale and large-scale modular construction necessitate management of effect factors in transportation and on-site work. However, in case of small-scale modular construction, the necessary modules for the on-site work have already been produced, it is not possible to manage the effect factors of factory. In case of large-scale modular construction, the effect factors on construction duration of the factory production should be managed even during construction process since the on-site work and the factory production are proceeded at the same time. Especially, problems, which occur when the factory production volume cannot follow the on-site work volume, arise only in the large-scale modular construction due to the simultaneous work of production, module lifting, and assembly(homas et al., 2000, Alvanchi et al., 2012). In short, if the the on-site work volume is greater than the factory production volume with no remaining modules in the storage, module lifting and assembly become impossible. In addition, the factory production stops because of insufficient storage yard for module when the factory production volume exceeds the on-site work volume. As mentioned earlier, with the assumption of the same volume between the factory production and on-site work, the size of storage yard determines the possibility of prior production in factory. Thus, it is necessary to compare the factory production volume with the on-site work volume even during the module production and lifting process. If the factory production volume is consistently greater than the on-site work volume, the size of the storage yard becomes the main management required variable, and acquisition of additional storage yard or transportation into the site will be the alternatives to solve those problems.

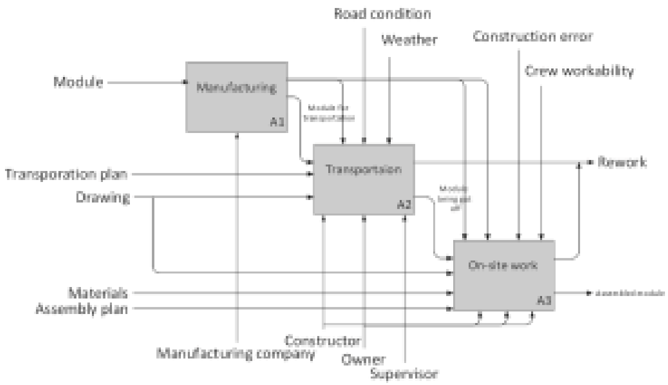

Fig. 3-4. IDEF0 level1 small scale modular construction

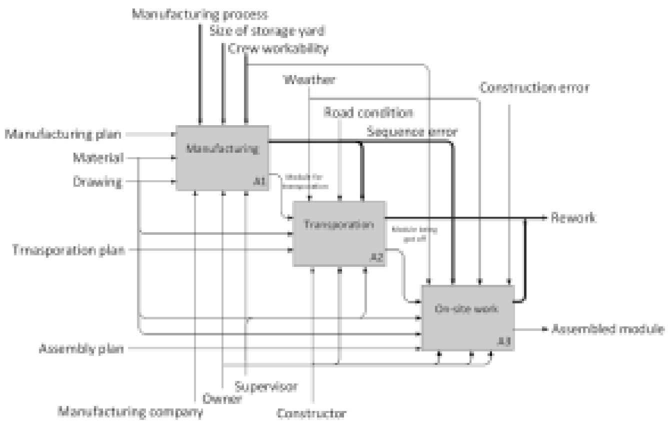

Fig. 3-5. IDEF0 level1 Large scale modular construction

At the A1 Level, rework from the site due to the factory production process might have continuous effect on the on-site work. Transportation following the factory production may not match with the construction order at the site and arise operation delay. Module delay and breakage due to the road condition during transportation also increase the possibility of delays and rework in the site. Construction errors at the site also causes the possibility of the construction duration delay. These causes eventually lead to reduction of on-site module volume and to construction duration delay. In addition, the impact on the site varies depending on the project scale. In case of small-scale modular, the cycle of factory production – transportation – on-site work is relatively small affecting less impact on rework due to factory production. But, in large-scale modular construction, the continuous and repeating cycle influences more onto rework. Also, small-scale modular construction completes the module production at the beginning, but large-scale modular construction proceeds simultaneous production at factory, which may reduce factory production volume due to effect factors of construction duration, leading to the on-site work delays. However, it is possible to set alternative change decision-making not only in the site but also in the factory. It is necessitated to select the best alternative among the alternatives of the factory and the site.

In conclusion, the following management factors are derived through

IDEF0 modeling. In case of large-scale modular construction, 1) if the volume of site construction exceeds that of factory production, shortage of the module may occur construction duration delay, and if factory production volume is excessive, the factory production process may stop due to lack of the storage yard. 2) Effect factors of respective phases from factory production and on-site work change the amounts of factory production and on-site work. 3) It is necessary to identify the optimal alternative among the alternatives in factory and the site during the alternative selection process.

3.2. Conceptual Framework of Quantity Management Model

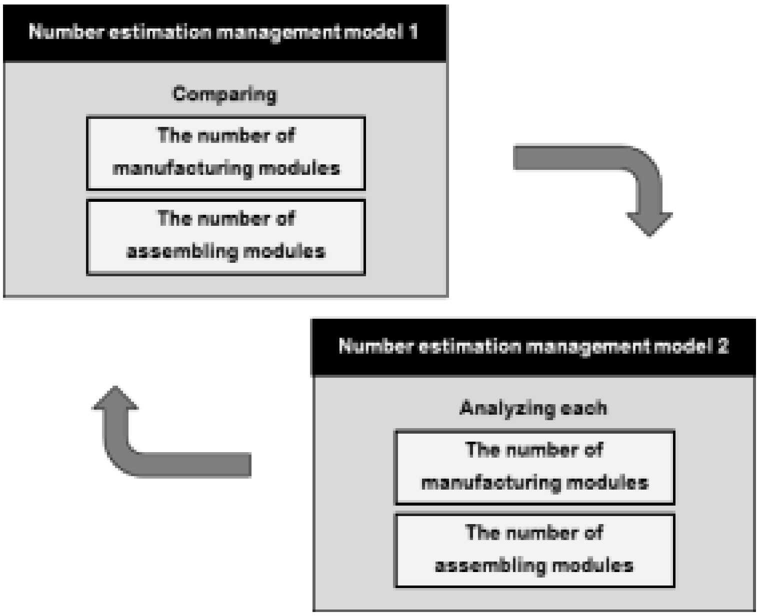

Fig. 3-6. Quantity Management Model framework

Modular construction is also necessary for change management like conventional construction. However, in modular construction it is difficult to manage change(Lu 2009). Therefore, it is necessary to manage and change the module manufacturing volume and assembling in site by the influence of change management. This model can be used for decision making. The factory production and on-site construction management model for decision making process in large-scale modular construction consists of two parts based on the three management factors derived through IDEF0 modeling. First, large-scale modular construction does not proceeds transportation and on-site work after complete production of modules but involves transportation and on-site work while producing modules, so it is required to compare and analyze the volume of factory production and the of on-site construction based on the storage yard. Second, it is necessary to determine the time reduction or delay of factory production and on-site work compared to the planning. Model frame work is as follow(Fig 10). The model 1 is a model that manages problems which occur when considerable difference between the manufacturing modules and the assembling modules arises the shortage of storage yard or of the number of modules remaining in the storage. Model 2 is a model that determines time reduction and construction delay by comparing actual manufacturing and assembling modules with the average manufacturing and assembling modules in the planning. Through Model 1, It is possible to determine the expected date of shortage of storage yard or the modules and to proceed the decision-making beforehand. Through Model 2, it is possible to proceed decision-making based on the expected delay or time reduction and required manufacturing modules or assembling modules. At this time, since excessive change of module numbers might lead to shortage of storage yard and remaining modules in storage, it is required to check through Model 1.

3.3. Formula Derivation Process for Quantity

To manage the manufacturing modules and assembling modules, data from the on-site work is expressed as variables.

Given Information

$$\mathrm{A} = \text{Number of module production per day(EA/day)}$$
$$\mathrm{B} = \text{Number of assembled module per day(EA/day)}$$
$$\mathrm{S} = \text{Area of storage yard}(m^2)$$
$$\mathrm{C} = \text{Number of module remaining(EA)}$$
$$\mathrm{s} = \text{Area occupied by one module}(m^2)$$
$$\mathrm{T} = \text{Total area occupied by modules} = (C + A - B) \times s(m^2)$$

In order to maintain factory production during construction, it is required to prevent stop production in factory and to retain remaining area of the storage yard not less than the area occupied by one module. Also, if transportation is assumed to be Just-in-time to prevent the on-site work delay caused by shortage of modules, the remaining modules in the factory must be maintained at a level that is greater than the number of assembling modules required per day.

Thus, if the number of modules manufactured per day is consistently greater than the number of modules assembled per day in the site, factory production will be stopped since the storage yard cannot hold all the manufactured modules at after a certain point. The following equation shows the calculation of the point.

$$D_1 = \left[\frac{S-T}{\{(A-B)\times s\}}\right](day) \text{ derived by this thesis}$$

Therefore, the decision-making process is required before reaching D1, and it is possible to solve the problem by reducing the number of daily manufacturing modules, increasing the number of daily assembling modules, or increasing the area of storage yard.

If the number of assembling modules is consistently greater than the number of manufacturing modules, the number of remaining modules in storage yard becomes smaller than the number of assembling modules in the site, resulting construction duration delay. The following equation shows the calculation of the point.

$$D_2 = \frac{C}{(B-A)}(day) \text{ derived by this thesis}$$

Therefore, it is required to proceed decision-making process before reaching D2, and reducing the number of assembling modules or increasing the number of manufacturing modules are the possible solutions.

In this part, expected delay period and expected shortening period are determined based on the planning of the manufacturing and assembling modules.

Given Information

$$\text{NM} = \text{Number of modules manufactured within } D_1(EA)$$

$$\frac{NM}{D_1} = \text{A}' = \text{Actual number of module production per daywithin } D_1(\text{EA/day})$$

If to determine the number of manufacturing modules, it is possible to derive planned number of module production per day(A) through the planned number of total modules(TM) and total duration(TD). The actual number of module production per day(A′) can be derived based on D1, the time duraction between the start of actual construction and current time point. Thus, if planned number of module production per day(A) exceeds the actual number of module production per day(A′), it is possible to derive expected delay period as shown below.

1) $\mathrm{A} - \mathrm{A}' > 0$

$$\frac{\{(A - A') * D_1\}}{A'} = Expected\ delay\ period(day)\ \text{derived by this thesis}$$

And, if planned number of module production per day(A) is smaller than the actual number of module production per day(A′), it is possible to derive expected shortening period.

2) $\mathrm{A} - \mathrm{A}' < 0$

$$\frac{\{(A' - A) * D_1\}}{A'} = Expected\ Shortening\ period(day)\ \text{derived by this thesis}$$

Also, it is possible to calculate the minimum module production per day after D1 to avoid delay (A″) based on the equations. It is necessary to increase the module production if the planned number of module production per day(A) exceeds the actual number of module production per day(A′). In the case, it is possible to derive the insufficient number of modules compared to the planned number of modules by calculating the difference between the daily planned production and the average of actual daily production and the time duration up to the moment. Thus, multiplication of the difference between the minimum daily production to recover the delay(A″) and planned number of modules to the remaining duration yields to the insufficient number of modules up to the moment. Therefore, the daily production to recover the delay is derived as follow. Likewise, if the actual daily average production exceeds the planned average daily production, required daily production (A″) after the moment to satisfy the planned construction duration can be calculated as follow.

1) $\mathrm{A} - \mathrm{A}' > 0$

$(A - \mathrm{A}') * D_1 = (\mathrm{A}'' - \mathrm{A}) * (\mathrm{TD} - D_1)$ derived by this thesis

$\mathrm{A}'' = \left\{(A - \mathrm{A}') * \frac{D_1}{\mathrm{TD} - D_1}\right\} + A$ derived by this thesis

$\mathrm{A}'' =$ Minimum module production after D_1 to avoid delay(EA/day)

$\mathrm{A}'' - \mathrm{A}' =$ The minimum manufacturing modules *to be increased*(EA /day)

2) $\mathrm{A} - \mathrm{A}' < 0$

$(A' - A) * D_1 = (\mathrm{A} - \mathrm{A}'') * (\mathrm{TD} - D_1)$ derived by this thesis

$\mathrm{A}'' = \mathrm{A} - \left\{(A - \mathrm{A}') * \frac{D_1}{\mathrm{TD} - D_1}\right\}$ derived by this thesis

$\mathrm{A}'' =$ Minimum module production after D_1 without delay(EA/day)

$\mathrm{A}' - \mathrm{A}'' =$ The maxinum modules to be decreased(EA/day)

In order to manage the number of modules in site, the same formula can be used by replacing the number of manufacturing modules with the number of assembling modules.

3.4. Summary

In this chapter, process modeling using IDEF0 was performed. Through this, the characteristics of small - scale modular architecture and large - scale modular construction were compared and the management plan in large - scale modular construction was derived. Based on this, a quantity management model for large - scale modular construction is presented. Based on the given information, this research derived a formula that can grasp the amount of manufacturing and the amount of assembly.

Chapter 4. Case Studies

In this Chapter, in order to confirm the validity of the management model using the formula derived by the process modeling. In this process, a real case of large-scale modular construction project was used as a case to analyze. In the project, the problems arise due to the different number of manufacturing modules and assembling modules. Using proposed management model, it was possible to suggest a standard of decision-making process to prevent the expected upcoming problems. Thus, among the alternatives considering both factory and the site, the optimal alternative solution which is possibly reduce the construction delay was selected.

4.1. Case of Large-scale Modular Construction Projects

Table 4-1. B project overveiw

Classification	Contents
Name	OOOO Construction Work
Location	Seoul Yongsan-gu Yongsan-dong 2
Building area	2,967,40 m^2
Total floor area	11,603,62 m^2
Story	4 stories
Purpose	Office
Structure	Steel Structure + Modular Unit(362 modules)

Among the domestic projects, B project was the largest single project. The planned construction duration for modules production in factory and lifting and assembling at the site were 40 days and 37 days respectively. The actual construction duration for the factory production and lifting and assembling at the site was 43 days and 43 days respectively. Also, it proceeded simultaneous process of the factory production and lifting and assembling for 37 days. Even though there was additional workforce input to the factory production and on-site work, construction delay was not avoidable.

It was not possible to attain the data of the actual daily number of production during the entire construction in the B modular construction project. Thus, the module number management model derived from this study will be applied to the construction duration delay problem which occurred at the beginning of the on-site work. Difference between the planned and actual number of manufacturing and assembling modules caused shortage of storage yard and led the factory production to stop, and it eventually arose the construction duration delay in the early stage of on-site work.

4.2. Model Application for Manufacturing

Based on the data of entire construction duration and the number of modules used in B project, the number of daily manufacturing modules and assembling modules are calculated as below.

Based on the data, (Table 4) shows the planned manufacturing and assembling modules and (Table 5) shows the actual manufacturing and assembling modules and data calculated by the management model. It is possible to confirm the factory production delay through Model 2.

Since the actual number of module production per day(A′) is smaller than the number of planned number of module production(A), it is possible to calculate the number of days delayed and the decreasing construction duration due to increasing manufacturing modules. Thus, the required production(A″) is calculated to prevent the construction delay. In the actual project, it drastically increased the number of manufacturing modules after the day 6, and shortage of storage was expected through the model 1. With expectation of shortage of storage yard on day 9, it is possible to proceed the decision-making process in advance. In the actual project, the shortage of storage yard was discovered on day 9 and stopped factory production on day 10 and 11.

Using the management model, it is possible to identify the delay of factory production, derive the number of manufacturing modules to recover the delay, and expect the shortage of storage yard beforehand. Therefore, it becomes possible to proceed the decision-making process to solve the problem before day 9.

Table 4-2. Planned variables in B project

Classification	Planned duration(days)	Total number of modules(EA)	Rete(/day)
Manufacturing	42	362	9.05
Assembling	37		9.78

Table 4-3. Planned the number of manufacturing and assembling modules

Day	1	2	3	4	5	6	7	8	9	10	11
Manufacturing(EA)	9	9	9	9	9	9	9	9	9	9	9
Cumulative total of manufacturing (EA)	9	18	27	36	45	54	63	72	81	90	99
Assembling(EA)	-	-	-	-	-	-	-	-	-	-	10
Cumulative total of assembling (EA)	-	-	-	-	-	-	-	-	-	-	10

Table 4-4. Actual the number of manufacturing and assembling modules

Day	1	2	3	4	5	6	7	8	9	10	11
Manufacturing(EA)	0	0	0	1	1	8	7	7	7	0	0
Cumulative total of manufacturing(EA)	0	0	0	1	2	10	17	24	31	31	31
Assembling(EA)	-	-	-	-	-	-	-	-	-	8	9
Cumulative total of assembling (EA)	-	-	-	-	-	-	-	-	-	8	17
A′(EA/day)	0.00	0.00	0.00	0.25	0.40	1.67	2.43	3.00	11.90	15.81	20.23
Delay (A-A′>0) (day)	-	-	-	124.00	95.00	22.80	16..06	13.33	11.90	15.81	20.23
A″(EA)	9.23	9.47	9.73	9.97	10.23	10.29	10.39	10.50	10.61	10.97	11.34
D1 with actual data (day)	-	-	-	-	-	2.63	2.00	1.00	0.00	-	-
D1 with A″=10 (day)	-	-	-	-	-	1.9	0.9	-	-	-	-

4.3. Virtual Case and Model Application for Assembling

Due to the lack of data, a virtual case was assumed and the model was applied. The hypothetical case assumption was based on actual construction data of the modular company. There were at least 28 to 49 differences in the amount of site construction every week, and 7.5 were built on an average daily basis. Based on the actual figures, we generated numbers and applied the model to verify the utility. Assembling in site was assumed to be the minimum of actual values due to weather deterioration. The manufacturing is factory is assumed to be less than the assembling in site because the module can be produced in a situation where the environmental impact is less than the site. It is assumed that 100 modules should be assembled. Assuming 20 modules remain in the yard, the maximum module capacity of storage yard is assumed to be 40 units.

Table 4-5. Virtual Case

Classification	Planned duration(days)	Total number of modules(EA)	Rete(/day)
Manufacturing	38	300	8.0
Assembling	40		7.5

Table 4-6. Virtual the number of manufacturing and assembling modules

Day	1	2	3	4	5	6	7	8	9	10	11
Manufacturing(EA)	8	8	8	8	9	9	7	7	8	8	8
Cumulative total of manufacturing(EA)	8	16	24	32	41	50	57	64	72	80	88
Assembling(EA)	6	5	5	6	6	5	6	5	6	6	6
Cumulative total of assembling (EA)	6	11	16	22	28	33	39	44	50	56	62
Average Manufacturing(EA/day)	8.00	8.00	8.00	8.00	8.20	8.33	8.14	8.00	8.00	8.00	8.00
Average Assembling(EA/day)	6.00	5.50	5.33	5.50	5.60	5.50	5.57	5.50	5.56	5.60	5.64
Modules in Storage Yard(EA)	22	25	28	30	33	37	38	40	42	44	46
Expected Delay Time(day)	16	16	16	14	13	12	11	10	9	8	7
Required Assembling(EA/day)	7.23	7.42	7.64	7.80	8.00	8.38	8.71	9.33	10.00	11.00	12.67

4.4. Result Analysis

In B project, the yard shortage problem could not be predicted and the factory work was stopped. However, using the model presented in this thesis, we could predict the shortage of the yard and the required production volume. As a result, time delays will be prevented or reduced.

In addition, the effectiveness of the model was verified assuming that the on-site work is less than planned in the virtual project. Based on the actual figures, the model was applied assuming the manufacturing and the assembling virtually. The application of the model predicted the shortage of yard, and calculated the expected delay due to the lack of on-site work and the assembling to make up for.

4.5. Summary

In this chapter, this research verified the effectiveness of the model using actual project and virtual project based on actual figures. In the case of real projects, using the model, this research were able to grasp the stoppage of manufacturing in advance, and were able to derive the output to compensate for the delay. In addition, it is assumed that there is a shortage of construction site in a virtual project. Based on this, it is possible to derive a construction amount to compensate for expected delay.

Chapter 5. Conclusion

5.1. Summary and Discussion

According to the survey reports of actual modular construction project, there is no significant difference of construction duration between the modular construction and convenient construction(IPA, 2015). This is due to the construction delay occuring during construction(Thomas et al., 2000, Alvanchi et al., 2012).

Current modular construction projects consider only site alternatives when selecting alternatives during change management(Kang 2006), and there is no established process for solving problems that occur during construction(Shin et al. 2016). In modular construction, it is difficult to respond to the change management at the site(Na Lu et al., 2009). Thus, applying the change management of the conventional construction, which mainly considers only the alternatives of the site, is an inefficient alternative selection process that does not consider the factory production, which accounts for 70-80% of the entire process. Hence, the alternative selection process of conventional construction leads to the interruption of the shortening the construction duration of modular construction.

Especially in case of large-scale modular construction, it is complicated to manage and identify the changes(Naoum, 1994, Zhen et al., 2009), and factory production is proceeded simultaneously with lifting and assembling(Lee, 2017). Alternative selection for the change management in the phase of construction also needs to be dualized. In addition, depending on the decision-making point, the effects of alternatives on factory and site change. Thus, it is required to consider the number of manufacturing modules and assembling modules at the same time as factory production is managed even during lifting and assembling at the site.

5.2. Contribution

This study identified the management factors of large-scale modular construction through IDEF0 modeling, and it developed management model for module volume which reflects the large-scale modular construction. By analyzing the construction delay of actual project, it was confirmed that the model presented in this study can be used to proceed the decision-making process before the construction delay occur. And it proposed efficient alternative which simultaneously consider the factory and the site.

This research carried out a study to improve the productivity of modular construction during construction phase. In addition, the viewpoints of change management at the factory and the on-site are suggested simultaneously. Finally, this research analyzed the characteristics of large - scale modular construction and proposed models for decision – making. In actual projects, site managers will be able to manage construction volume more efficiently using quantity management model developed in this thesis.

5.3. Limitation and Further Study

As the scope of study is limited to the process of manufacturing and assembling modules and to the construction period, management model after assembling and the cost and quality, which are the major management factors, are not addressed. Therefore, it will be necessary to develop a decision-making process that considers cost and quality as well as the construction duration in the further studies.

Bibliography

Alazzaz, F., & Whyte, A. (2014). “Uptake of off-site construction: benefit and future application.” World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8(12), pp. 1219-1223.

Alvanchi, A., Azimi, R., Lee, S., AbouRizk, S. M., & Zubick, P. (2011). “Off-site construction planning using discrete event simulation.” Journal of Architectural Engineering, 18(2), pp. 114-122.

Andras M. (2015).“The Lure of Modular Construction-Assessing the Advantages and Risks.” IPA Newsletter.

Carlson, D. O. (Ed.). (1995). “Automated builder: dictionary/encyclopedia of industrialized housing.” Automated Builder Magazine, Publications Division, CMN Associates.

Cho, J., Jang, O., Yu, J., & Lee, M. J. (2014). “Development of Change Management System for Urban Development Project.” Korean Journal of Construction Engineering and Management, 15(2), pp. 79-86.

Cho, B. H., Kim, H. J., & Ko, G. H. (2007). “The state of art in the modular construction in Korea.” Journal of Korean Society of Steel Construction, 19(1), pp. 112-119.

Giaglis, G. M. (2001). “A taxonomy of business process modeling and information systems modeling techniques.” International Journal of Flexible Manufacturing Systems, 13(2), pp. 209-228.

Hammer, M., & Champy, J. (2009). “Reengineering the Corporation: Manifesto for Business Revolution.” A. Zondervan.

Hofman, E., Voordijk, H., & Halman, J. (2009). “Matching supply networks to a modular product architecture in the house-building industry.” Building Research & Information, 37(1), pp. 31-42.

Ibbs, C. W., Wong, C. K., & Kwak, Y. H. (2001). “Project change management system.” Journal of Management in Engineering, 17(3), pp. 159-165.

Kang, Sung-O. (2007). “A Study on the process analysis and setting up normal duration of large scale military modular building”, MS thesis, Mokwon University, Korea.

Kim T. Y., Park M. S., Lee H. S., Seo S. U., Lee J. H. and Kim S. Y. (2013). “Optimization Methodology of Modular Unit Factory Production Process Using DSM”Journal of Architecture Institute of Korea, 29(6), pp. 113-122.

Kim, M., Park, M., Lee, H. S., Lee, J., & Lee, K. P. (2015). “Development of Manufacturing Planning for Multi Modular Construction Project based on Genetic-Algorithm.” Korean Journal of Construction Engineering and Management, KICEM, 16(5), pp. 54-64.

Kim M. J., Lee H. K, and Kim J. J. (2006) “An Analysis of Cost Management Process Using IDEF0”Journal of Architecture Institute of Korea, 22(4) pp. 177-185.

Ko, H. U., & Park, H. K. (2009). “A Study of Development of Change Process for Configuration Management in Construction Project Management.” Journal of the Korean Society of Civil Engineers, 29(1D), pp. 81-89.

Lawson, M., Ogden, R., & Goodier, C. (2014). “Design in modular construction.” CRC Press.

Lee. H. S., Song S. H., and Kim U. Y. (2002), “Process Redesign for Material Management by Analyzing Information.” Journal of Architecture Institute of Korea, 18(11), pp. 125-132.

Lee J. H. (2017) “Planning and Control of Modular Building Construction Projects Using Discrete Event Simulation.”Doctoral thesis, Department of Architecture and Architectural Engineering The Graduate School of Seoul National University.

Mullens, M. A. (2011). “Factory Design for Modular Homebuilding: Equipping the Modular Factory for Success.” Constructability Press.

Lu, N. (2009). “The current use of offsite construction techniques in the United States construction industry.” In Construction Research Congress 2009: Building a Sustainable Future, pp. 946-955.

Naoum, S. G. (1994). “Critical analysis of time and cost of management and traditional contracts.” Journal of Construction Engineering and Management, 120(4), pp. 687-705.

Pinto, J. K., & Kharbanda, O. P. (1995). “Lessons for an accidental profession. Business Horizons.”, 38(2), 41-50.

Hao, Q., Shen, W., Neelamkavil, J., & Thomas, R. (2008). “Change management in construction projects.” NRC Institute for Research in Construction, NRCC-50325.

Stickel, B. S. R. E. (1996). “Business Process Modelling.”Springer-Verlag, 319, 1.

Shin H. K., and Ahn Y. H. (2016) “Modular Building Construction Process Development by Benchmarking International Best Practices.”Korean Journal of Construction Engineering and Management, KICEM, 17(6), pp. 3-12.

Smith, R. E. (2010). “Prefab Architecture.” A guide to modular design and construction.

Thomas, H. R., & Sanvido, V. E. (2000). “Role of the fabricator in labor productivity.” Journal of construction engineering and management, 126(5), pp. 358-365.

Velamati, S. (2012). “Feasibility, benefits and challenges of modular construction in high rise development in the United States: a developer's perspective.” Doctoral thesis, Massachusetts Institute of Technology.

Zhao, Z. Y., Lv, Q. L., Zuo, J., & Zillante, G. (2009). :Prediction system for change management in construction project.“ Journal of Construction Engineering and Management, 136(6), pp. 659-669.

Appendix

A. ICOM Matrix for Small-scale Modular Construction Project

ICOM Matrix

Level0	Level1	Level2	Input	Control	Mechanism	Output
A0:Small-scale modular construction	A1:Manufacturing	A11:야적	검사된 완성 모듈		제작사	운송 준비 완료 모듈
	A2:Transportation	A21:상차	운송 계획, 운송 준비 완료 모듈		시공사	상차된 모듈
		A22:점검	도면, 운송 계획, 상차된 모듈		시공사, 발주처, 감리	점검 완료 모듈, 재작업
		A23:운송	운송 계획, 점검 완료 모듈	운송순서 오류, 도로 상황, 날씨	시공사	운송 완료 모듈, 재작업
		A24:하차	운송 완료 모듈	운송순서 오류	시공사	하차 완료 모듈, 재작업
	A3:On-site work	A31:점검	도면, 양중계획, 하차 완료 모듈		시공사, 발주처, 감리	점검 완료 모듈, 재작업
		A32:양중	도면, 양중계획, 점검 완료 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	양중 된 모듈, 재작업
		A33:설치	양중계획, 양중 된 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	설치 된 모듈, 재작업
		A34:조립	자재, 도면, 설치 된 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	조립 완료 모듈, 재작업

B. ICOM Matrix for Large-scale Modular Construction Project

ICOM Matrix

Level0	Level1	Level2	Input	Control	Mechanism	Output
A0:Large-scale modular construction	A1:Manufaturing	A11:생산 전 작업	자재, 도면, 생산계획	작업능력, 생산 프로세스	제작사	바닥 및 골조 완성 모듈
		A12:생산	자재, 도면, 생산계획, 바닥 및 골조 완성 모듈	작업능력, 생산 프로세스	제작사	완성 모듈, 재작업
		A13:점검	도면, 생산계획, 완성 모듈		제작사, 발주처, 감리	검사된 모듈, 재작업
		A14:야적	생산계획, 검사된 완성 모듈	야적장 넓이	제작사	운송 준비 완료 모듈
	A2:Transportation	A21:상차	운송 계획, 운송 준비 완료 모듈		시공사	상차된 모듈
		A22:점검	도면, 운송 계획, 상차된 모듈		시공사, 발주처, 감리	점검 완료 모듈, 재작업
		A23:운송	운송 계획, 점검 완료 모듈	운송순서 오류, 도로 상황, 날씨	시공사	운송 완료 모듈, 재작업
		A24:하차	운송 완료 모듈	운송순서 오류	시공사	하차 완료 모듈, 재작업
	A3:On-site work	A31:점검	도면, 양중계획, 하차 완료 모듈		시공사, 발주처, 감리	점검 완료 모듈, 재작업
		A32:양중	도면, 양중계획, 점검 완료 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	양중 된 모듈, 재작업
		A33:설치	도면, 양중계획, 양중 된 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	설치 된 모듈, 재작업
		A34:조립	자재, 도면, 설치 된 모듈	양중순서 오류, 시공 오류, 날씨, 작업능력	시공사	조립 완료 모듈, 재작업

국 문 초 록

모듈러 건축은 공장 생산 과정을 토해서 품질과 정확도를 향상시킬 수 있고 같은 유닛을 반복적으로 만들어내기 때문에 대규모 생산과 비용 절감이 가능하다. 특히, 현장 작업과 공장 생산을 동시에 진행 할 수 있기 때문에 공기 단축이 가능하다. 그러나 실제 모듈러 건축 프로젝트 조사 보고서에 따르면 모듈러 건축과 기존 건축의 평균 공사 기간에서는 큰 차이를 보이고 있지 못하다. 이는 모듈러 건축 프로젝트의 실제 시공 시 발생하는 공기 지연 문제 때문이다. 따라서 실제 시공 시 공기 지연 방지를 위한 대안 선택이 필요하며, 특히 대규모 모듈러 건축 프로젝트 현장 시공의 경우 현장에서의 모듈 양중 및 조립 과정이 공장 생산과 동시에 진행되기 때문에 대안 파악이 공장과 현장을 동시에 고려하여 수행되어야 한다. 본 연구에서는 규모에 따른 모듈러 건축의 실제 시공 시 프로세스의 차이를 토대로 IDEF0 모델링을 통하여 대규모 모듈러 건축의 관리 요소를 파악하였고 이를 이용하여 공기 지연을 판단할 수 있는 공장 생산량과 현장 시공량 관리 모델을 개발하였다. 이를 이용하여 대규모 모듈러 건축 실제 시공 시 발생하는 공기 지연 문제를 감소시킬 수 있을 것이다.

키워드: 모듈러 건축, 의사결정, 변경 관리, 건설 관리

학 번: 2016-21089