Doctor of Philosophy

Crew Allocation Based Scheduling Method for Modular Construction Project

August, 2019

Department of Architecture & Architectural Engineering
The Graduate School of
Seoul National University

Hosang Hyun

Abstract

Crew Allocation Based Scheduling Method for Modular Construction Project

Hosang Hyun

Department of Architecture & Architectural Engineering
The Graduate School of Seoul National University

In developed countries, such as the United States, Australia, and Singapore, the construction industry is suffering from labor shortage and a declining number of new entrants, which can cause project schedule and cost overrun. Modular construction is an effective approach to overcoming this problem, and consists of unit production processes and on-site work processes. The unit production comprises a significant proportion of the work in a project and is conducted in a factory. Hence, the efficiency of general

manufacturing can be utilized to good effect. Therefore, the modular construction method offers benefits, such as low cost, short construction duration, high quality, and improved safety, which are based on high productivity in the manufacturing process. However, modular construction is labor intensive, and the lack of expertise in the management of modular construction is related to cost and schedule overrun. Hence, to improve the labor productivity, and to conduct modular projects over a tightly scheduled duration, a crew allocation-based schedule is required. Moreover, concurrently conducted unit production and on-site work require flexibility in the project schedule, which increases the complexity of scheduling. To solve the scheduling problems in the complex process of modular construction, a systematic scheduling method is required. Therefore, this dissertation aims to propose a crew allocation-based scheduling method for modular construction that can cope with flexibility. To achieve this objective: 1) First, an integrated planning process is suggested with a focus on reducing changes in the schedule caused by rework. Using this process, feedback and reverse information flow is reduced. This is related to reduced rework in a project, which implies a reduced change in schedule, and the planning process is a starting point for modular project scheduling. 2) Then, a multi-objective optimization model for modular unit production line design is developed based on crew allocation. Using the optimization results, various unit production line design alternatives can be suggested based on crew

allocation. 3) Finally, an on-site work scheduling method is suggested. By applying the suggested on-site work scheduling method, constraints on the adjustment of on-site work production rate can be overcome. Through adjustment, the on-site work duration and allocated number of workers can be reduced. The suggested unit production and on-site work scheduling method show improvement in terms of both cost and time. Therefore, the result of this dissertation can contribute to mitigating the labor shortage problem and to dealing with the flexibility in modular construction project schedules. As an academic contribution, this dissertation improves our understanding of modular construction complexity. Through the development of an optimization and simulation model, various project schedule alternatives and project planning schemes can be evaluated in a controlled simulation environment. However, this dissertation has the following limitations: 1) the scheduling methods exclude resources other than labor, 2) a unit assembly line design method can be applied to continuous production, 3) works similar to stick-built construction are not considered, and 4) the manufacturing and on-site work scheduling methods are not connected.

Keywords: Modular Construction, Crew Allocation, Scheduling, Flexibility, Off-site, Multi-Objective Optimization, Discrete Event Simulation, Dependency Matrix Structure

Student Number: 2014-31098

CONTENTS

Chapter 1 Introduction 1

1.1 Research Background 1

1.2 Problem Statement 3

1.3 Research Objective 7

1.4 Research Scope 10

1.5 Organization of Dissertation 13

Chapter 2 Preliminary Study 19

2.1 Modular Construction Method.. 19

2.2 Crew Allocation Based Scheduling...................................... 25

2.3 Flexibility in Modular Construction Schedules 28

Chapter 3 Integrated Planning Process Focusing on Reducing Rework 31

3.1 Planning Process for Modular Construction 31

3.2 Causes of Rework in Modular Projects 35

3.2.1 Rework in Construction Projects 35

3.2.2 Rework in Modular Construction Projects..........................36

3.2.3 Lack of Experience and Expertise in Modular Construction 39

3.2.4 Dependency Structure Matrix 42

3.3 Information Flow Identification in Planning Phase 45

3.3.1 Activities in Construction Design Process..........................45

3.3.2 Causes of Rework in Modular Construction.......................47

3.3.3 Identification of Information Flow for DSM 50

3.4 Integrated Planning Process for Modular Construction......... 56

3.4.1 Schematic Design Phase 56

3.4.2 Design Development Phase 57

3.4.3 Construction Documentation Phase....................................58

3.4.4 Manufacturing, Transportation, and On-site Work Planning Phase...59

3.5 Summary 62

Chapter 4 Multi-Objective Optimization for Modular Unit Production Line Design... 65

4.1 Unit Production and Multi-Objective Optimization 65
4.2 Multi-Objective Production Line Design............................. 69
4.2.1 Production Line Scheduling in Manufacturing Industry.....69
4.2.2 Modular Unit Production Line Design................................70
4.2.3 Multi-Objective Optimization for Unit Production Line 72
4.2.4 Optimization Methodology 74
4.3 Multi-Objective Optimization Model for Continous Modular Unit Production Line(MOMUPL) Development........................... 78
4.3.1 Problem Description 78
4.3.2 Problem Formulation 79
4.3.3 GA for MOMUPL..83
4.4 Case Studies 88
4.5 Initialization for MOMUPL 96
4.5.1 Initialization Procedure Experiment 106
4.6 Discussions 111
4.7 Summary 112

Chapter 5 On-site Work Scheduling Method Using Parallel Station Method 115

5.1 Modular Construction On-site Work 115

5.2 Repetitive Scheduling Method for Modular Construction On-site Work 118

5.2.1 Constraints of On-site Work Schedule 118

5.2.2 Construction Scheduling Methods for Repetitive Projects 121

5.2.3 Adjustment of Production Rate in Repetitive Schedule....126

5.2.4 Parallel Station Method..128

5.3 On-site Work Scheduling Model Development 130

5.3.1 Model Development...130

5.3.2 Model Verification 133

5.4 Simulation Experiments 137

5.4.1 Simulation Information...137

5.4.2 Simulation Result Analysis 141

5.5 Modification of Scheduling Methods 143

5.6 Discussions 146

5.7 Summary 147

Chapter 6 Conclusions 149

6.1 Summary 149

6.2 Contributions 152

6.3 Limitations 154

6.4 Application of Suggested Scheduling Method 157

Bibliography 161

Appendix 173

Abstract (Korean)... 195

LIST OF TABLES

Table 2-1 Drivers of modular construction project....................................23

Table 2-2 Constraints on modular construction projects 24

Table 3-1 Activities in the design phase...46

Table 3-2 Cases and causes of rework in modular construction projects.....48

Table 3-3 Mitigation work plan for reducing rework..................................49

Table 3-4 Activity relationship based on information flow..........................51

Table 4-1 Notations and constraints for MOMUPL...................................81

Table 4-2 Example of work information..89

Table 4-3 Optimization Experiment Parameters...90

Table 4-4 Information on solutions on Pareto front 1.................................91

Table 4-5 Optimization results for unit production line...........................109

Table 5-1 Previous research on repetitive scheduling methods 128

Table 5-2 Project information for modular construction project 132

Table 5-3 Number of workers inputted to model......................................135

Table 5-4 Model verification results...136

Table 5-5 Simulation information and results of scheduling methods......140

Table 5-6 Idle time in TACT method according to cycle time.................142

Table 5-7 Simulation results for LOB+P and P+LOB..............................145

Table A-1 Activity Information on Production Line.................................174

Table A-2 Example of Optimized Production Line Design.......................180

LIST OF FIGURES

Figure 1-1 Modular construction process..2

Figure 1-2 Flexibility in modular construction projects................................8

Figure 1-3 Research process..17

Figure 1-4 Framework of modular construction scheduling method 18

Figure 2-1 Interrelated project phases in modular construction...................21

Figure 2-2 Repetitive modular construction process 26

Figure 2-3 Workspace interference in modular units 27

Figure 3-1 Modular construction benefits and influence of rework..............36

Figure 3-2 Temporary organization in a modular project 41

Figure 3-3 Information relationships in a DSM...44

Figure 3-4 Information flow identification using DSM................................54

Figure 3-5 Rearranged activities by optimization..55

Figure 4-1 Examples of modular unit production line design 71

Figure 4-2 Solution sorting procedure in NSGA-II......................................77

Figure 4-3 Encoding schema of MOMUPL 84
Figure 4-4 Crossover operator of MOMUPL 85
Figure 4-5 Mutation operator of MOMUPL 85
Figure 4-6 Diagram of crowding distance 87
Figure 4-7 Optimized production line solutions in Pareto front 90
Figure 4-8 Example of optimized production line 93
Figure 4-9Comparison of results for multi and single objective optimization..95
Figure 4-10 Initialization procedure for MOMUPL......................................99
Figure 4-11 Diagram of decision making in initialization procedure...........103
Figure 4-12 Examples of crew reallocation and modification of maximum number of workers 105
Figure 4-13 Optimization Result for MOMUPL with Initialization Procedure...108

Figure 5-1 Repetitive work in stick-built and modular construction..........120
Figure 5-2 Idle time in repetitive schedule according to work load 121
Figure 5-3 Activity relationship in CPM 123
Figure 5-4 LOB scheduling method and idle time between activities........124
Figure 5-5 Reduced idle time in TACT scheduling method 126

Figure 5-6 Idle time in TACT scheduling method....................................126

Figure 5-7 Crew allocation in parallel station method 130

Figure 5-8 Parallel station method for modular construction on-site work 130

Figure 5-9 Modular construction on-site work process in simulation model...132

Figure 5-10 On-site work process for TACT applying the PSM..................139

Figure 5-11 Production rate modification in LOB+P 144

Figure 5-12 Process of modified scheduling method...................................144

Chapter 1. Introduction

1.1 Research Background

In the developed countries, such as United States, Australia, and Singapore, the construction industry is suffering from a labor shortage problem and a declining number of new entrants, which could contribute to project schedule and cost overrun (Arif et al., 2002; Lu, 2009). Modular construction is an effective approach to overcoming this problem. Modular construction consists of unit production processes and on-site work processes (Eastman and Sacks, 2008; Mullens, 2011; Shaked and Warszawski, 1992). Unit production comprises a significant proportion of work in a project and is conducted in a factory, which is a controlled environment. Hence, the efficiency of general manufacturing can be utilized to good effect. Therefore, the modular construction method offers benefits, such as low cost, short construction duration, high quality, and improved safety, which are based on the high productivity of the manufacturing process. Figure 1-1 illustrates the modular construction process and shortened project duration (Lawson et al., 2014). Given its high productivity, modular construction can alleviate the labor shortage problem in the construction industry.

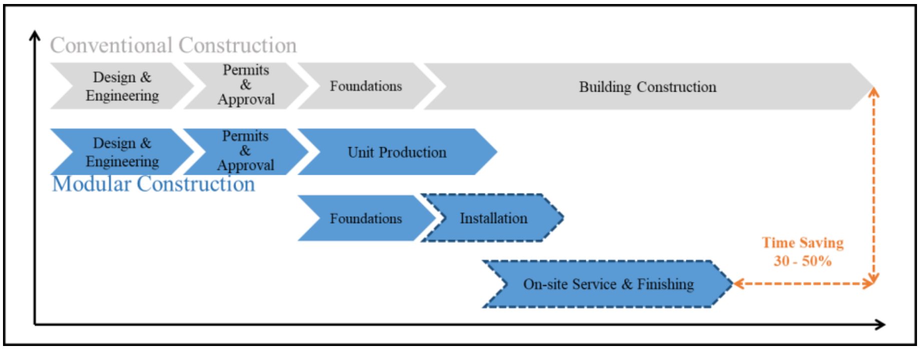


Figure 1-1. Modular construction process.

Among the various benefits, the major drivers for the usage of modular construction are reduced labor resource requirements and short project durations (Blismas and Wakefield, 2009). To apply these benefits to the construction project, the uptake of modular construction in the construction industry has increased. However, modular construction is also labor intensive and requires a sophisticated management process to complete projects in a short duration (Al-Bazi and Dawood, 2010; Arif et al., 2002; Lu, 2009). In other words, labor resource allocation and the project schedule should be the main considerations when planning a modular project.

Crew allocation can be defined as the process of assigning workers to ensure that they are utilized in an optimal way (Al-Bazi and Dawood, 2010). In construction project scheduling, by adjusting the crew allocation plan, project duration, collapses between works, and idle time are all reduced (Nassar, 2011). However, the crew allocation-based scheduling problem becomes more challenging when it includes a complex process such as modular construction (Al-Bazi and Dawood, 2010; Alvanchi et al., 2011). In a modular construction project, unit production and on-site work are conducted simultaneously, and the project duration is generally reduced by this concurrent work. For example, when manufacturing units, temporary work, earth work, foundation work, and on-site work for finishing units can be conducted simultaneously. The overlapped duration changes depending on the project's characteristics and is determined in the planning phase. Therefore, a scheduling method for modular construction can ensure flexibility in the schedule. This flexibility allows for various schedule alternatives and requires that the unit production and on-site work schedules can cope in each alternative. In summary, it is necessary for the production rate of each work type to be adjustable, and a wide range of adjustments ensures flexibility.

1.2 Problem Statement

The current utilization of modular construction in the construction industry is limited and experiencing shortcomings in terms of delivering products at a competitive cost and time (Al-Bazi and Dawood, 2010; Blismas et al., 2005; Lu, 2009). This is because current modular construction is based on the scheduling and planning strategy of conventional stick-built construction; however, modular construction requires special methods of production technology. The application of stick-built construction scheduling methods to modular construction generates inappropriate crew allocation plans and causes time and cost overrun (Moghadam et al., 2012). When scheduling modular projects using conventional methods, project duration, unit production, and on-site work rate can be defined as constraints. For example, even if more workers or resources are allocated to on-site work, if the unit production rate cannot be increased, the project duration cannot be shortened, and idle time occurs in the on-site work schedule. If the on-site work production rate cannot be increased, the unit production rate also cannot be increased due to the constraint of unit storage space. Therefore, the work schedules must cope with flexibility to be balanced with each other. However, there are limitations when using conventional scheduling methods for modular construction, and they are listed as follows:

1) **Absence of integrated planning process based on information flow to include project participants**

   In the planning phase, information and requirements from participants, such as architect, unit production, and on-site work contractors, are integrated. After this integration, the project manager determines the requirements that should be considered in the building design. Then, based on the design, a building specification is determined, and work planning is established. The work planning includes determining the proportions of unit production and on-site work and when the production should start. Based on these proportions, a project schedule is established. Thus, this planning process can be defined as the starting point of project scheduling, and sophisticated information management skills and advice are required to facilitate project progress (Gibb, 2000). Previous studies suggested the application of the work planning to design phase but do not suggest any comprehensive planning processes. (Blismas and Wakefield, 2009; Blismas et al., 2005; Johnsson and Meiling, 2009; Lawson et al., 2014; Nahangi et al., 2014; Smith, 2011). Moreover, lack of knowledge and experience make early advice for planning and scheduling unavailable (Blismas et al., 2005). Therefore, the absence of a comprehensive process is related to engineering rework in the planning phase and field rework. This rework causes changes to the schedule and loss of labor productivity.

2) Difference between job shop scheduling (JSS) and unit production line scheduling and necessity of various production schedule alternatives

JSS in the manufacturing industry and unit production line scheduling in production line design are similar in that they are both combinatorial problems. However, the difference is that unit production scheduling is a combinatorial problem of cycle time and crew allocation, whereas JSS involves a sequence of operations, and the order of machinery use is combined and optimized. Therefore, the scheduling methods in the manufacturing industry cannot be applied to unit production line design. Moreover, single-objective optimization cannot provide various production schedules. Thus, this optimization cannot deal with the flexibility of modular construction schedules.

3) Increase in idle time and limited range of production rate of on-site work caused by using the scheduling method for stick-built construction

When scheduling a project using repetitive scheduling methods, such as line of balance (LOB) and TACT, the schedule is optimized by production rate adjustment of each work. However, when applying repetitive scheduling methods to modular on-site work, constraints, such as different work amount of activities and workspace, limit the range of production rate adjustment. Therefore, idle time in the schedule cannot be optimized, and the on-site schedule cannot embrace the flexibility of modular construction schedules.

1.3 Research Objective

To overcome the abovementioned problems and limitations, the objective of this dissertation is to suggest a systematic planning process to schedule modular construction projects based on crew allocation. The planning process is developed to deal with the flexibility of modular construction schedules. Figure 1-2 illustrates the two types of flexibility in modular construction projects that are considered in this dissertation. Flexibility of work proportion indicates the change in the work proportions of unit production and on-site work. These proportions change depending on the project characteristics, such as site environment, transportation conditions, and constraints on production and on-site work. The proportions are determined in the early planning phase and are directly related to the work schedule. Flexibility of overlapped duration indicates the duration of simultaneous works of unit production and on-site work. This duration is also changed depending on the project characteristics or project goal; by adjusting the duration, various schedule alternatives can be generated. Therefore, it is necessary for the unit production and on-site work schedules to be capable of coping such alternatives. Therefore, the research objectives of this dissertation are as follows:

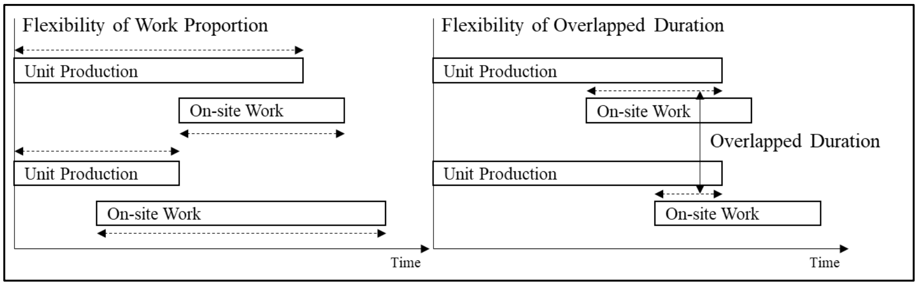


Figure 1-2. Flexibility in modular construction projects.

1) First, a modular construction planning process is suggested. This process includes design, unit production, and on-site work, and the interrelationship between each work type is described. The planning process is based on information flow of project participants and feedback process, and rework in the project can be reduced by improving the information flow using a dependency structure matrix (DSM). The planning process includes a procedure to determine the proportions of unit production and on-site work and to establish production and on-site work planning.

2) Secondly, a model to design a unit production line is developed. To deal with the flexibility in the overlapped duration, multi-objective optimization is used to suggest various production schedules with a focus on reducing labor resources and duration concurrently. By using the model, production rate can be adjusted, meaning the unit

production schedule can cope with various project schedule alternatives.

3) Finally, an on-site work scheduling method is proposed to deal with flexibility in the overlapped duration, and a simulation model is developed to experiment on different scheduling methods. To cope with the flexibility, the range of production rate of on-site work is extended using the parallel station method. Using simulation model, the required labor resources and duration according to different scheduling methods can be estimated. The on-site work schedule can be balanced with various unit production or project schedule alternatives using the extended range of production rates.

By accomplishing the objectives, a modular construction schedule can be suggested, and various schedule alternatives can be generated. Therefore, a particular schedule can be established depending on the project characteristics, and flexibility in the schedule can be included in project planning.

1.4 Research Scope

The objective of this dissertation is to propose a systematic scheduling method for modular construction projects with a focus on crew allocation. To exclude influences from other factors and to maintain a uniform experimental environment, the following research scope and assumptions are established:

1) Modular construction has been used to overcome various constraints, such as the labor shortage problem, shortage of infrastructure for construction, and extreme site conditions. This dissertation focuses on suggesting a crew allocation-based scheduling method to alleviate the labor shortage problem. Therefore, the results of this dissertation can be used effectively in developed countries that suffer from the labor shortage problem.

2) The research objective of this dissertation is to propose a modular construction scheduling method that allows flexibility. Therefore, works that are similar to stick-built construction, such as temporary work, foundation work, and earth work, are excluded from this dissertation.

3) This dissertation details parts of the modular construction process, such as planning, unit production, and on-site work, where the flexibility of modular construction should be considered when schedule each work.

4) A unit production line design method is developed for a continuous unit production line. Because this type of line can produce units in a shorter duration than the static type. Moreover, the continuous type is based on the just in time (JIT) principle, meaning it can cope with daily on-site demand. Finally, a factory is a continuous unit production line that can produce units for multiple project with less impact than the static type.

5) In unit production and on-site work schedules, labor resources are considered a major variable that affects schedules by adjusting the number of workers. In these schedules, crew combination for conducting certain work is not considered, and the number of workers for conducting work is considered for crew allocation.

6) There are various types of modular unit and building. In this dissertation, hexahedral units (box type), which have steel structure, is investigated. Therefore, infill and panel type modular building is

excluded.

Based on the established scope and assumptions, a scheduling method for modular construction is developed. A detailed scope and assumptions for each work schedule development are given in the following chapters.

1.5 Organization of Dissertation

This dissertation consists of six chapters, and brief descriptions of each chapter are as follows. Figure 1-3 illustrates the research process for scheduling modular construction projects.

Chapter 1: In this chapter, the research background and flexibility in modular construction schedules are briefly described. Then, the problem statement, objective, scope, and assumption of this dissertation are established.

Chapter 2: In this chapter, to understand the modular construction method, a literature review is conducted. In this literature review, the importance of crew allocation and flexibility in modular construction projects is described.

Chapter 3: In this chapter, a planning process for modular construction is proposed. This process includes design, unit production, on-site work planning. The interrelationship between each work planning is described, and information flow is improved using a DSM. The proposed process focuses on reducing the feedback process and rework. The process also includes a procedure to determine the proportions of unit production and on-site work. The procedure can be a starting point for scheduling modular construction projects.

Chapter 4: In this chapter, a model to design a modular unit production line is developed. The model focuses on multi-objective optimization, where the objectives are maximization of unit production and minimization of inputted workers. The optimization results are represented as production line design solution sets. Each solution has the unique information used to design the production line as well as different production schedules, such as unit production for certain durations and numbers of inputted workers. By using various solution sets, the unit production schedule can handle flexibility in the schedule.

Chapter 5: In this chapter, an on-site modular construction scheduling method is proposed. In this scheduling method, to overcome the production rate constraints, the parallel station method (PSM) is applied. By using the PSM, the range of production rates can be extended, helping the on-site work schedule to cope with various schedule alternatives. To validate the proposed method, a simulation model is developed, and a case study is conducted. The results show that the proposed scheduling method is more efficient in terms of project duration and labor cost than the scheduling method for stick-built construction.

Chapter 6: In this chapter, this dissertation is summarized. The contributions and limitations are described. Future research is also suggested to improve the research in this field.

Figure 1-4 shows the research framework for scheduling modular construction projects. To establish crew allocation-based schedules for modular construction projects, unit production and on-site work plans are required. These plans are established using an integrated planning process. In the planning process, design, unit production, and on-site work processes are integrated, and the order of activities in each process is rearranged to reduce feedback and inverse information flow. As an output of the integrated planning process, a rearranged planning process is suggested, and the project manager can use this process to plan unit production and on-site work. The planning process includes a phase to determine the proportions of unit production and on-site work. Therefore, the rearranged planning process can be a starting point for unit production and on-site work scheduling. After the proportions are determined, the work activities for unit production and on-site work are determined. Based on these activities, unit production and on-site work schedules are established. To schedule unit production, a unit production line design method is proposed, and a multi-objective optimization model is developed. As an output of the unit production schedule, a set of production line design alternatives is suggested, and the alternatives include information, such as the number of allocated workers and production duration. The project manager can choose alternatives depending on their project's characteristics, such as the whole modular project duration, assigned duration for unit production, and production rate of on-site work. Then, an on-site work schedule is established to complete the assigned activities. As input data, the assigned activities, number of units, and productivity of workers are required. Then, the on-site work is scheduled using repetitive scheduling methods, and to extend the range of production rate, a parallel scheduling method is applied. As an output of the on-site work schedule, on-site work duration and the number of allocated workers are suggested depending on repetitive scheduling methods. By using the unit production and on-site work scheduling methods proposed in this dissertation, modular construction projects can be scheduled, and the number of allocated workers can be estimated.

Introduction

- Research Background
- Problem Statement
- Objectives and Scope

Preliminary Study

- Modular Construction Method
- Crew Allocation Based Scheduling
- Flexibility in Modular Construction Schedule

Integrated Planning Process

- Planning Process for Modular Construction
- Causes of Rework in Modular Project
- Information Flow Identification
- Integrated Planning Process

Crew Allocation Based Scheduling Method

Unit Production

- Unit Production and Multi-Objective Optimization
- Multi-Objective Production Line Design
- Model Development
- Case Studies
- Initialization for MOMUPL

On-site Work

- Modular Construction On-site Work
- Repetitive Scheduling Method for Modular Construction
- Model Development
- Simulation Experiment
- Modification of On-site Scheduling Methods

Conclusions

- Summary of Research
- Contributions
- Future Research

Figure 1-3. Research process.

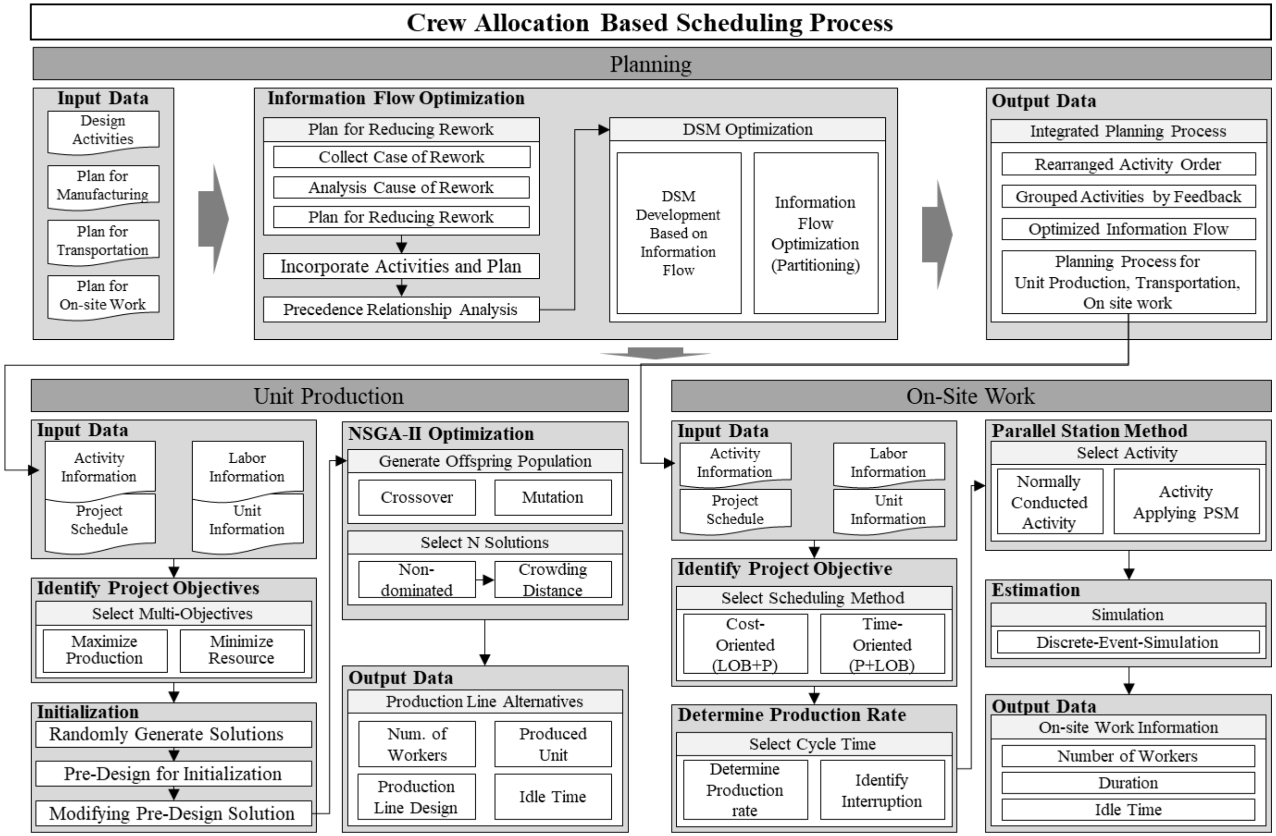


Figure 1-4. Framework of modular construction scheduling method.

Chapter 2. Preliminary Study

2.1 Modular Construction Method

The construction industry, which is labor intensive, is constrained by the site environment conditions and continues to lag behind other industries in terms of technological adoption and integration. Modular construction is recognized as an innovative process in the construction industry (Boyd et al., 2012). As there are many benefits of modular construction methods, modular construction is chosen as construction method by various drivers (Blismas and Wakefield, 2009). Table 2-1 lists the drivers of modular construction. The various drivers mean modular construction can be applied to various project types, such as cost-oriented, time-oriented, and safety-oriented projects. Moreover, multi-objective projects can also be conducted by combining their benefits. For example, in developed countries, high labor costs can be offset by using modular construction methods, which means modular construction can be used to alleviate the labor shortage problem in the construction industry (Blismas and Wakefield, 2009).

Modular construction consists of planning, unit production, transportation, and on-site work processes. A significant proportion of the work is conducted in an environmentally controlled manufacturing system.

Hence, the risk of site conditions can be reduced, and the project performance can be improved by applying the high productivity of the manufacturing industry (Smith, 2011). After modular unit production, the units are transported to the construction site and assembled on the foundation. Then, to complete the building construction, the on-site works, such as finishing work, are conducted. The unit production and on-site work can be conducted simultaneously, reducing the project duration (Lawson et al., 2014).

However, in spite of the many benefits and drivers, the uptake of modular construction is still limited. The reasons for this stem from the complexity of modular construction methods and lack of modular construction expertise. Modular construction has complex project processes resulting from intermediate unit manufacturing processes (Alvanchi et al., 2011). The complex processes cause problems such as late and out-of-sequence deliveries, fabrication errors, and incompatible fabrication rate of on-site assembly operations (Alvanchi et al., 2011; Thomas and Sanvido, 2000).

In terms of project scheduling, the unit production and on-site works are conducted simultaneously, and each schedule should be balanced to prevent interruption from the other. Therefore, when planning modular projects, scheduling unit production and on-site work requires 1) an iterative feedback process between participants of each work process (Blismas and Wakefield, 2009), 2) sophisticated management skills to manage the information flow between participants (Alvanchi et al., 2011; Lu, 2009; Smith, 2011), and 3) early decisions to plan the simultaneous work (Johnsson and Meiling, 2009; Nahangi et al., 2014; Smith, 2011). To meet the requirements, project participants should be integrated in the early project phase (Lawson et al., 2014).

These requirements make the scheduling process more challenging. Moreover, as shown in Figure 2-1, each phase of a modular construction process is interrelated, which makes the process more complex. Therefore, to schedule and conduct modular construction, expertise in modular construction management is required.

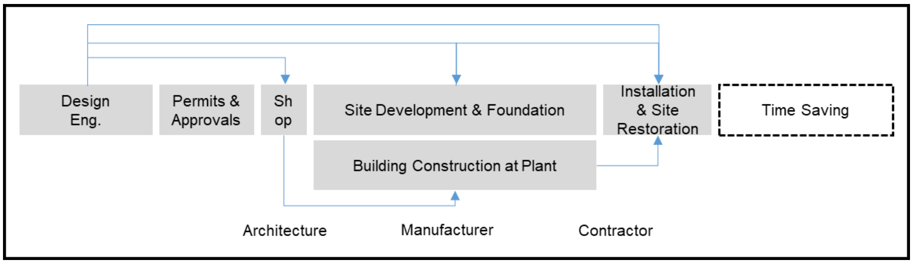


Figure 2-1. Interrelated project phases in modular construction.

However, in the construction industry, there is a lack of expertise in modular construction (Blismas et al., 2005). Table 2-2 lists the constraints on modular construction. Almost all of the constraints stem from a lack of management knowledge and expertise in modular construction (Blismas et al., 2005). This lack of knowledge and expertise means that modular construction's benefits cannot be utilized or the performance would be lower than expected (Al-Bazi and Dawood, 2010). The lower performance is negative for modular construction, which hinders the uptake of modular construction.

Table 2-1. Drivers of modular construction project (Blismas et al., 2005).

Drivers of Modular Construction Projects				
Cost	Time	Quality	Health & Safety	Sustainability
Ensuring project cost certainty	Ensuring project completion date is certain	Achieving high quality	Reducing health and safety risks	Reducing environmental impact during construction
Minimizing non-construction costs	Minimizing on-site duration	Achieving predictable quality		Maximizing environmental performance throughout the lifecycle
Minimizing construction costs	Minimizing overall project time	Achieving performance predictability throughout the lifecycle of the facility		Implementing "respect for people" principles
Minimizing overall lifecycle costs				

Table 2-2. Constraints on modular construction projects (Blismas et al., 2005).

Constraints on Modular Construction Project		
Site Constraints	Process Constraints	Procurement Constraints
Restricted site layout or space	Short overall project timescales	Project team members have no previous experience of OSP
Multi-trade interfaces in restricted work areas	Unable to freeze design early enough to suit OSP	Obliged to work with a particular supply chain
Limited or very expensive skilled on-site labor	Limited capacity of suppliers	Not willing to commit to a single point supplier
Problems transporting manufactured products to site	Not possible for follow-on projects to use the same processes	Obliged to accept lowest cost rather than best value
Live working environment limits site operation	No opportunity for component repeatability on current or future projects	Key decisions already made preclude OSP approach
Limitation in movement of OSP units around site		Limited expertise in off-site inspection
Site restricted by external parties		Early construction/manufacturing expertise and advice unavailable
		Obliged to accept element costing based on SMM

2.2 Crew Allocation Based Scheduling

One of the major drivers and benefits of modular construction is reduced labor resource requirements (Blismas and Wakefield, 2009). Crew allocation can be defined as the process of assigning crews of workers to ensure that they are used in an optimal way (Al-Bazi and Dawood, 2010). To utilize the benefits of this, labor utilization must be considered in modular construction schedules, and the schedule must be based on crew allocation to reduce labor resources.

The other reason that the schedule must be based on crew allocation is repetitiveness of modular construction. The modular construction process is characterized by a sequence of critical tasks that are repeated in each of the modular units (Moghadam et al., 2012; Shaked and Warszawski, 1992). The similar modular units are produced on a production line, and the activities on the production line are repeated in every cycle time. In on-site work, after the units are transported to on-site, they are assembled, and on-site work, such as finishing work, is conducted. Therefore, the characteristics of modular construction can be defined as repetitiveness. Figure 2-2 shows repetitive works in a modular construction project.

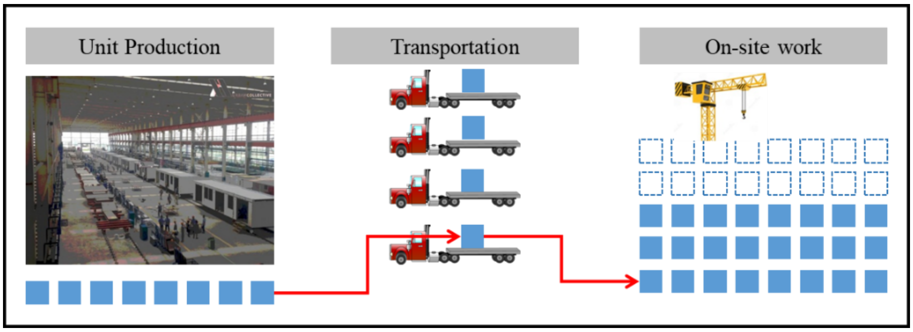


Figure 2-2. Repetitive modular construction process.

In the construction industry, repetitive activities, such as high-rise buildings, pipeline networks, and highway projects, are found commonly. In this repetitive work, crews are allocated to activities and conduct activities sequentially, moving from one repetitive unit to the next (El-Rayes and Moselhi, 1998). Because of frequent crew movement, construction projects that consist of repetitive activities should be scheduled to enable prompt movement of crews among the repetitive units to minimize idle time and bottlenecks (El-Rayes and Moselhi, 1998). Therefore, in repetitive works, the schedule should be based on crew allocation and should facilitate maintaining 1) a constant production rate, 2) continuity of work, 3) time buffers between activities, and 4) stage buffers (Reda, 1990).

When scheduling repetitive projects, the requirements for repetitive work are satisfied, and the idle time between activities is reduced by adjusting the production rate of each activity (Al-Bazi and Dawood, 2010). When adjusting production rate, the crew allocation is also modified. However, in modular construction, there is a constraint on the adjustment of crew allocation. This constraint is work space interference and occurs when conducting unit production and on-site work, as shown in Figure 2-3. For example, when increasing production rate by allocating more workers, workspace interference may occur and productivity may decrease. Therefore, the number of workers that can be allocated to each unit should be determined according to the characteristics of the activity. This constraint is imposed on adjustment of production rate in unit production and on-site work.

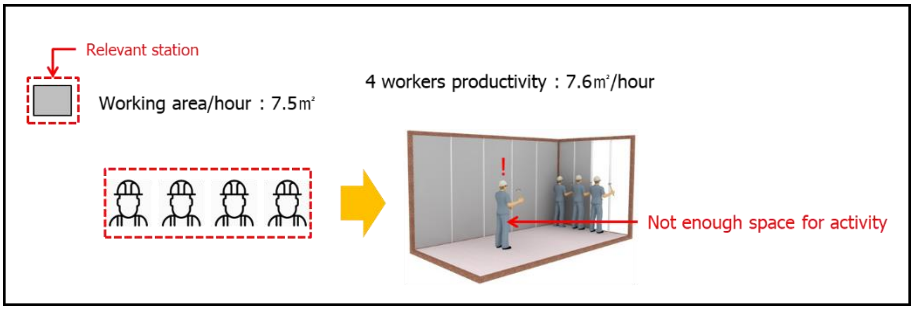


Figure 2-3. Workspace interference in modular units.

2.3 Flexibility in Modular Construction Schedules

There are challenges to maintaining the conditions for repetitive work when scheduling modular construction. In modular construction projects, unit production and on-site work are conducted simultaneously for a certain duration, and the overlapping duration is determined by the project's characteristics. In other words, various project schedule alternatives can be generated according to the overlapped duration, and the project manager can choose among them. Therefore, modular construction scheduling has flexibility. Moreover, by adjusting the work proportions of unit production and on-site work, more schedule alternatives can be generated, which is the another cause of schedule flexibility.

Figures 1-1 and 1-2 show the two types of flexibility in the schedule according to the overlapped duration of works and work proportions. When unit production and on-site work must be conducted concurrently, the production and on-site work rates should be balanced to prevent interruption to the schedule. When balancing the schedule, crew allocation can be a very complex problem because many constraints must be considered, such as possible production rates of each work, unit storage space for the scheduling buffer, and total project duration. Moreover, to utilize the benefit of repetitiveness, the interruption between each work should also be minimized to maintain the conditions for repetitive works (Al-Bazi and Dawood, 2010). When the schedules for unit production and on-site work are not balanced, these problems are expected 1) late and out-of-sequence unit deliveries, 2) incompatible unit production rates of on-site unit assembly, and 3) excessive unit storage space (Alvanchi et al., 2011). To realize its benefits, a modular construction schedule should be able to embrace flexibility allowed by the balance in schedule in that one of the major drivers and benefits of modular construction is shortened project duration.

Production line scheduling methods in previous studies, which have focused on single-objective optimization problems, can only suggest one best solution. Although this single solution has improved performance, the solution cannot cope with flexibility. In terms of on-site work, in the scheduling methods for conventional stick-built construction, production rate of works can also be adjusted by modifying the crew allocation plan. However, these methods cannot consider constraints on modular construction, such as workspace limitations and difference in work amount for each on-site work activity. Therefore, when using conventional scheduling methods to schedule modular projects, idle time may occur, and the schedule cannot cope with flexibility without a decrease in labor productivity.

Therefore, to deal with flexibility, a scheduling method for modular construction is required to suggest various unit production and on-site work schedule alternatives.

Chapter 3. Integrated Planning Process Focusing on Reducing Rework

3.1 Planning Process for Modular Construction

In the previous chapter, the flexibility of modular construction schedules was investigated. The proportions of off-site and on-site work is the one of the factors causing flexibility in the planning phase because the proportions are not standardized but are determined according to project characteristics, such as on-site environment, project constraints, and project duration. Based on these proportions, a project schedule is established and work plans, such as unit production, transportation, on-site work, and resource allocation planning, are determined. To determine the proportions, modular building design is required, and requirements of participants are included in the design phase. In this phase, a significant proportion of errors cause rework, and errors are caused by omitted, inaccurate, and incomplete information exchange (Love and Li, 2000; Love et al., 1999). This rework causes changes in planning, designing, manufacturing, and on-site work schedules and affects cost, schedule, quality, and performance of a project (Hwang et al., 2009; Love et al., 2002; Love and Li, 2000; Love et al., 1999; Nahangi et al., 2014; Park and Ock, 2016; Smith and Jirik, 2006). Moreover, modular projects are more affected by changes because inability to make changes is the top barrier of using the modular construction method (Lu, 2009; Smith, 2011).

To reduce rework, it is necessary for project participants to integrate and coordinate from the early planning phase before conducting design (Blismas and Wakefield, 2009; Smith, 2011). In modular construction, however, the intermediate manufacturing process increases information flow complexity in the planning phase (Alvanchi et al., 2011). When incorporating designing, manufacturing, and on-site work planning into the planning phase, the information flow complexity increases because of the feedback process among participants, such as the designer, manufacturer, and constructor for on-site work. This increased complexity makes the information relationships difficult to identify (Lu, 2009; Smith, 2011). The complex information flow makes cooperation difficult in the early planning process. For the integrated planning, many studies have been conducted (Han et al., 2014; Lawson et al., 2014; Lawson and Richards, 2010; Moghadam et al., 2012; Mullens, 2011; Olearczyk et al., 2014; Park and Ock, 2016; Smith, 2011). Previous studies have suggested the application of each work planning to the design phase but do not suggest comprehensive design processes, such as the related design phase, where the work planning should be considered along with which information should be included in the sub-design phase (Blismas and Wakefield, 2009; Blismas et al., 2005; Johnsson and Meiling, 2009; Lawson et al., 2014; Nahangi et al., 2014; Smith, 2011). For example, if the Road Traffic Act regulation of a corresponding area is not considered in related design phases, rework may occur to revise the design of units, such as unit size to transport the unit to on-site. Although comprehensive design and planning processes are required, the complexity of modular construction makes it difficult to plan modular projects in the early phase. Moreover, the lack of expertise in modular construction on the market makes early advice unavailable in the planning phase (Blismas et al., 2005). The absence of integrated design processes for modular construction is related to a decrease in project performance.

Therefore, the objective of this chapter is to suggest an integrated planning process, including designing, unit production, and on-site work planning with a focus on reducing reworking in modular projects. To achieve the objective, the activities in the design process of stick-built construction are first analyzed in a literature review to modify the process for modular construction. Then, the major issues causing rework in modular construction are analyzed, and work planning to reduce rework is identified. To integrate the design process and work planning, the information flow and relationship between activities in the design and work planning processes are identified. Based on the information flow and relationship, the sequence of activities is rearranged using DSM. Finally, an integrated design process is proposed.

This chapter focuses on the major issues that cause field rework related to manufacturing and on-site work and engineering rework related to design and planning activities. The scope of the design process in this research is limited to the activities related to architectural mechanical, structural, electrical design of buildings and includes site analysis in the early design phase.

By achieving this objective, it is expected that the integrated design process can complement the modular construction planning process and can alleviate the lack of understanding and expertise of modular construction. Hence, rework in modular construction projects can be reduced by allocating a mitigation plan in the planning phase to manage major issues related to rework. The expected academic contribution of using DSM is that the information flow in the process can be identified, and the information feedback process can be reduced.

3.2 Causes of Rework in Modular Projects

3.2.1 Rework in Construction Projects

Rework is the unnecessary effort of redoing a process or activity that was incorrectly implemented the first time (Love and Li, 2000). Rework affects the cost, schedule, and quality of construction projects, as illustrated in Figure 3-1. The direct cost of rework is estimated to be from 2 to 12 % of total construction costs, so rework must be managed (Hwang et al., 2009; Josephson and Hammarlund, 1999; Love and Li, 2000; Love et al., 1999; Smith and Jirik, 2006). To reduce rework in construction projects, the causal relationship and effect of rework are analyzed (Burati Jr et al., 1992; Love and Edwards, 2004; Love et al., 2002; Love et al., 1999; Love et al., 1999; Rahmandad and Hu, 2010). Typically, a significant proportion of rework is caused by errors made during the design process. These errors appear downstream in the procurement process and therefore have a negative impact on a project's performance (Love and Edwards, 2004; Love et al., 2002; Love and Li, 2000; Love et al., 1999). The causes of errors in the design phase are omissions from the project brief; ineffective or lack of coordination; inaccurate, incomplete, or conflicting documents; and an unrealistic design schedule (Love et al., 1999). To reduce errors in the design phase, it is necessary for participants to be integrated and coordinated in the early design phase, and it is recommended that quality management is implemented in the design phase (Hwang et al., 2009; Love and Li, 2000; Love et al., 1999).

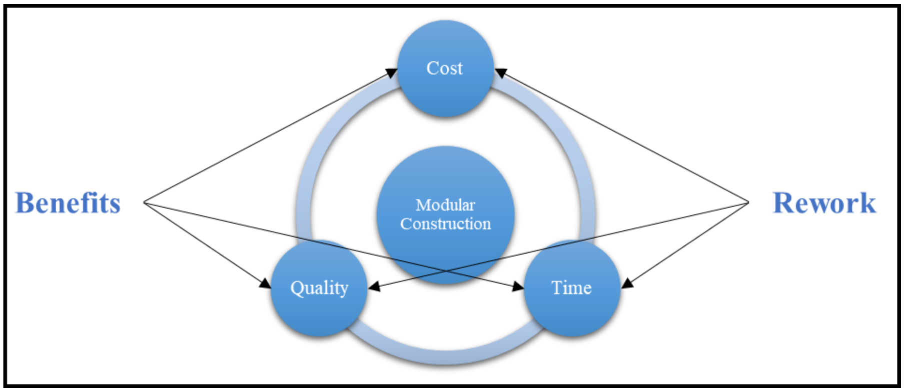


Figure 3-1. Modular construction benefits and influence of rework.

3.2.2 Rework in Modular Construction Projects

In modular construction, rework affects the project performance, and a mitigation plan to reduce rework must be considered in the design and planning phases (Blismas et al., 2005; Lu, 2009; Smith, 2011). Although modular construction has the benefit of short construction period, simultaneously conducted unit production and on-site work in the project execution contributes to rework. The concurrent work makes the complexity of work processes increase. This complexity is related to errors in the design and planning phases. Moreover, for concurrent work, details such as building design, transportation plan, and unit assembly method should be determined in the early design phase. The determination of unit production and on-site work planning in the early design process means an inability to make changes on-site and requires the utilization of massive amounts of previous project information (Blismas et al., 2005; Lu, 2009). As a short time-to-market is becoming more important in today's construction industry, processes are started before their predecessors are completely finished, which means projects are executed without full determination of the details (Arashpour et al., 2013). Taking an element back to be reworked is cost prohibitive in modular construction. If not coordinated properly, modular construction can cost much more than in on-site construction (Al-Bazi and Dawood, 2010; Arif et al., 2002; Blismas et al., 2005; Lu, 2009; Shaked and Warszawski, 1992; Smith, 2011). Hence, in modular construction, the early design and planning phases are important to improve project performance and to reduce rework (Johnsson and Meiling, 2009; Nahangi et al., 2014; Smith, 2011). In the initial design process in modular construction, project participants should be involved to determine the details that increase complexity of information flow between participants in the design process (Lawson et al., 2014; Nahangi et al., 2014; Smith, 2011). Therefore, the integrated design and planning process, which can be used in the early project phase, is required to consider the information flow to facilitate early decision making among project participants (Alvanchi et al., 2011; Lu, 2009; Smith, 2011).

To reduce rework in modular construction, many studies have been conducted to consider unit production and on-site work planning in the early project phase. Nahangi et al. (2014) asserted that there is a need to continuously monitor the manufacturing process to avoid rework and suggested automated comparison of laser scanning data with 3D CAD models to detect inaccuracies. To reduce rework in the design and planning phase when considering a tower crane operation plan, tower crane location and path optimization models have been suggested (Han et al., 2014; Lei et al., 2013; Olearczyk et al., 2014). Smith (2011) suggested the major issues and guidelines for unit production, transportation, and on-site work planning and analyzed the effect of design and planning change in the early stage. However, the above studies do not suggest the information relationship between each planning and do not suggest an integrated design process including work planning of each activity, which can cause rework or a feedback process in the design and planning phase. The rework or feedback process is related to field rework. To reduce rework, many studies have focused on integration of project participants. Blismas and Wakefield (2009) argued that the benefit of modular construction can only be realized when it is incorporated as the central approach from the design stage. Park and Ock (2016) suggested some major causes related to rework and argued that rework in modular construction occurs because of deficient interface management in the design, unit production, and on-site installation processes, as well as immaturity of modular technology. Smith (2011) argued that to integrate the participants in the early project phase and to improve information flow, the delivery method should also be considered and that the integrated delivery methods, such as integrated project delivery (IPD), can improve project performance. In modular construction, to use integrated delivery methods, integrated design skills and understanding are required to ensure that system interfaces are managed and designed for production, erection, and performance (Blismas et al., 2005). However, there is limited expertise in the marketplace of off-site construction methods and its processes among designers and constructors (Blismas and Wakefield, 2009). The limited expertise of participants is related to the cause of uncertainty in the design phase generated by inaccurate information, such as missing, unreliable, inaccurate, and conflicting information (Love et al., 1999). Because of the deficiency of understanding, approaches to the design process are still largely based on traditional methods, which are unsuited to modular construction (Blismas and Wakefield, 2009).

3.2.3 Lack of Experience and Expertise in Modular Construction

In modular construction, design and specification should be frozen in the early stage to conduct unit production and on-site work concurrently

(Blismas et al., 2005). Moreover, changes are not as freely permitted without cost, especially once unit production has commenced (Blismas and Wakefield, 2009). Hence, more integrated skill and understanding are required to determine the details with minimized change of planning (Blismas et al., 2005). However, there are few modular construction experts with management knowledge and experience, and unexperienced participants are related to rework in modular projects. The cause of limited expertise is the nature of modular construction. In modular construction, on-site work is usually conducted by a general contractor in the local area. The temporary and intermittent modular project execution of the general contractor hinders the accumulation of knowledge and experience. The lack of experience and knowledge of a general contractor are related to rework and are the barrier to using modular construction (Blismas et al., 2005; Gibb, 2000; Lu, 2009; Schoenborn, 2012). Temporary execution means temporary project organization composition. Contrary to the stick-built construction method, in the modular construction method, the construction project is conducted in a factory and on-site, which means works are conducted by different participants. Therefore, the divided participants have temporary organization, as illustrated in Figure 3-2. Although defects are ascribed to individuals, the basic cause can be found in organizational phenomena because the organization is temporary and the participants only take part for a limited time, which is related to a lack of motivation (Josephson and

Hammarlund, 1999). In terms of the organization problem, rework is caused by lack of motivation. Most rework caused by carelessness is due to a lack of motivation (Josephson and Hammarlund, 1999).

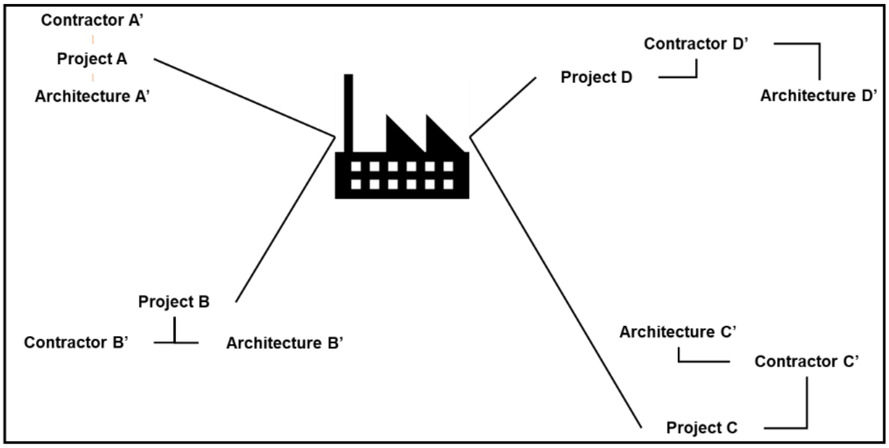


Figure 3-2. Temporary organization in a modular project.

In summary, the temporary organization problem hinders the accumulation of knowledge and experience and causes a lack of motivation. Therefore, to overcome this problem, an integrated design and planning process that can guide the project participants from the early project phase is required.

3.2.4 Dependency Structure Matrix

The integrated planning process, including designing, unit production, and on-site work planning, is required to overcome the limited experience of participants and to guide modular construction projects by establishing an information relationship between each activity. To suggest the integrated planning process, it is necessary for the activity information flow to be managed to identify the information relationships and to facilitate information flow between activities.

Network analysis and bar chart techniques for planning construction work have been used extensively, but they are not capable of dealing with iterations in the design process, such as feedback processes between activities (Austin et al., 2000). To represent and solve the problem caused by information flow in the design process, IDEF0 is used. IDEF0 is useful to model the system process based on the relationship between activities. However, IDEF0 does not also have the capability to manage the feedback process and iterations in the system (Giaglis, 2001; Mayer et al., 1995).

In modular construction, DSM was used to improve the work flow of the unit production process based on the precedence relationship between activities on the production line (Lee et al., 2017). DSM was used to identify the information flow and iterations within the design process and to schedule activities with the objective of optimizing the task order (Austin et al., 2000). After identifying information flow, DSM reallocates the order of activities to reduce the number of feedback processes (Austin et al., 2000; Oloufa et al., 2004). Therefore, DSM can be used to suggest an integrated planning process based on the information relationship and to optimize the order of activities for reducing feedback processes in the planning process of modular construction.

In the DSM, the relationship among activities can be characterized by three fundamental building blocks: parallel (independent), sequential (dependent), and coupled (interdependent), as shown in Figure 3-3 (Austin et al., 2000). After the relationship is identified based on the relationship type in the DSM, optimization is conducted to reduce the feedback and iteration processes in the system by reallocating the activity order (Austin et al., 2000). There are algorithms for process optimization in a DSM, such as partitioning, tearing, and clustering. In this research, a partitioning algorithm that can reduce the feedback processes based on the information flow by reallocating the activity order is used (Austin et al., 2000).

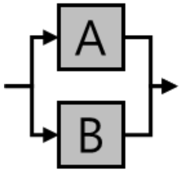
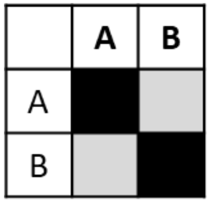
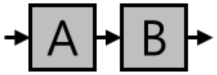
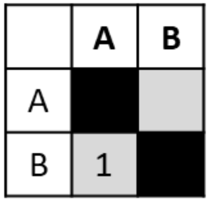
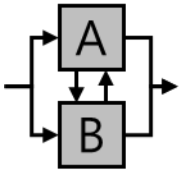
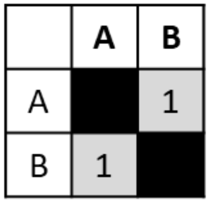
Interaction Type	Representation		Description
	Graph	DSM	
Parallel			• There is no information on the interaction between activities, and each activity is independent.
Sequential			• This is a dependent relationship, where activity A is the predecessor. • Activity B is dependent on Activity A.
Coupled			• Activity A and B exchange information and have an interdependent relationship. • This relationship represents the occurrence of feedback in the design process.

Figure 3-3. Information relationships in a DSM.

3.3 Information Flow Identification in the Planning Phase

3.3.1 Activities in Construction Design Process

To propose an integrated planning process, information flow between activities in the design, manufacturing, and on-site work planning is identified. Based on this information flow, a DSM is established, and the planning process is optimized using a partitioning algorithm. The activities in the design process involve the activities for the stick-built construction design process. The reason for this is that the design process can be used by unexperienced participants of modular construction. The scope of the design process includes schematic design (SD), design development (DD), and construction documentation (CD). The activities in the design process are limited to the activities related to determination of architectural, structural, electrical, and mechanical design. The activities in the design process are listed in Table 3-1. In the schematic design phase, the alternatives of site layout planning are suggested based on the site analysis results in the pre-design phase. Then, materials and a structural system are applied to each design alternative. The alternatives are prepared to be selected in the design development phase. In the design development phase, the building design is selected among design alternatives, and the final design is developed. In this phase, materials that will be applied to design are selected. Each project participant reviews the electrical, mechanical, and structural systems through the feedback process between participants. In the construction documentation phase, based on the documents in the design development phase, the details of the building are determined, and MEP and a structural system are documented for construction. The results of the CD phase are used for construction, so the results are crosschecked between project participants in the design phase, and the errors and omissions in the documentation and constructability are checked.

Table 3-1. Activities in the design phase.

Design Phase	ID	Activities
SD	1	Site analysis
	2	Site layout planning
	3	Establish design direction in terms of plan, section, and elevation
	4	Building core planning
	5	Explore interior and exterior material
	6	Review the strengths of materials, structural design criteria, and design load
	7	Review alternatives of structural system design, such as size of components (rough estimation of unit weight)
	8	MEP planning and MEP space requirement review
DD	9	Develop and modify the schematic design
	10	Determine interior and exterior materials
	11	Determine structural system design
	12	Structural design analysis and structural calculation documentation
	13	Draft the locations and sizes of structural components
	14	Bar arrangement drawing documentation
	15	Determine MEP system
	16	Review MEP and structural component interference

CD	17	Prepare construction document of the design
	18	Structural and MEP system adjustment and documentation
	19	Architectural detail, specifications, structural calculation documentation and incorporate subcontractor's documentation
	20	Principal structural parts finishing propriety review
	21	Check errors and omissions in documentation and constructability review

3.3.2 Causes of Rework in Modular Construction

To include a plan to reduce rework in the planning process, causes of rework are identified. Then, the mitigation plan is established. The cases and causes of rework are collected from a daily report of modular construction projects, which documents details of work activities and issues, as shown in Table 3-2. The mitigation plans related to the causes of rework are derived from the analyses of previous studies. The activities that should be conducted to reduce engineering rework in the planning and designing phase are also included in the mitigation plans (Lawson et al., 2014; Smith, 2011). The mitigation plans related to rework from the daily report are described in Table 3-3. For example, the rework caused by fireproof paint applied to connection for unit assembly occurs because the fireproof paint should not be applied to the connection. It is anticipated that the structural performance of the painted connection may decrease. Therefore, rework is conducted to remove the fireproof paint from the connection, and the unit is reassembled. This rework means that the interference between fireproof painting and connection is not marked in the shop drawing for unit manufacturing. The interference is checked when preparing shop drawings in the manufacturing planning phase.

Table 3-2. Cases and causes of rework in modular construction projects.

Related Phase	Cause of Rework
Manufacturing	Interference between MEP and structural components
	Fireproof paint application to connection
	Rework caused by error of activity order on manufacturing line
	Excess manufacturing tolerance
	Quality deterioration in manufacturing process
Transportation	Damage and deformation in transportation
	Revision of design caused by omission of reviewing Road Traffic Act in the design process
On-site Work	Interference between MEP and structural components, such as concrete foundations
	Damage to unit caused by on-site work interference
	Shortage of passage space for workers in PIT
	Occurrence of component tolerance errors
	Occurrence of tolerance error in MEP
	Unit deformation caused by unit lifting
	Damage caused by weather conditions on un-proofed components

Table 3-3. Mitigation work plan for reducing rework

Related Phase	ID	Cause of Rework
Manufacturing	22	(Production plan) Determine and review the work activities for unit production in the factory (determine factory work)
	23	(Production plan) Prepare shop drawings and check interference of unit production
	24	(Production plan) Prepare unit production line design
	25	(Quality management plan) Prepare manufacturing tolerance management plan
	26	(Quality management plan) Prepare quality management plan
Transportation	27	(Transportation plan) Prepare management plan for reducing deformation and damage
	28	(Transportation plan) Review the Road Traffic Act regulations (weight and size of unit)
On-site Work	29	(On-site work plan) Determine the on-site work activities
	30	(On-site work plan) Select tower crane location
	31	(On-site work plan) Select tower crane specification
	32	(On-site work plan) Prepare shop drawings and check for interference
	33	(On-site work plan) Review constructability for on-site work
	34	(Quality management plan) Prepare on-site work tolerance management plan
	35	(Quality management plan) Prepare deformation management plan in unit lifting process
	36	(Quality management plan) Prepare unit proofing plan to reduce damage from weather conditions

3.3.3 Identification of Information Flow for DSM

To include the rework mitigation plan in the planning process for modular construction, it is necessary for the information flow between activities to be identified. Through this identification, the activities in the integrated design and planning process can be rearranged to facilitate the information flow. In Table 3-4, the information flow between activities in the planning phase is identified by a literature review of previous studies. (Park and Ock, 2016; Park et al., 2012; Smith, 2011). Each activity in Table 3-4 has a predecessor. The predecessor column lists the IDs of the activities that must be conducted before each activity. In other words, the activity can only start with the information obtained by completing the predecessor activities. For example, when planning site layout, it is necessary for activities, such as site analysis, reviewing the Road Traffic Act regulation, and tower crane location selection, to be preceded. However, when selecting tower crane location, site layout planning is a predecessor, which means there is a feedback process between the site layout planning and tower crane location selection. Therefore, when conducting the activities, activity information, such as building and crane location, should be exchanged and shared. Moreover, the Road Traffic Act regulation review follows the activity of site layout planning while also providing the site layout planning activity with information. The reverse information flow means there is a possibility of engineering rework in the design and planning phase. The feedback and reverse information flow can be reduced by rearranging the activity order in the optimization of the design process. The order is rearranged based on information flow.

Table 3-4. Activity relationship based on information flow.

Related Phase	ID	Activities	Predecessor
Schematic Design	1	Site analysis	—
	2	Site layout planning	1, 28, 30
	3	Establish design direction in terms of plan, section, and elevation	2, 4, 28
	4	Building core planning	3
	5	Explore interior and exterior material	3
	6	Reviewing the strength of material, structural design criteria, and design load	1, 3
	7	Reviewing alternatives of structural system designs, such as sizes of component (rough estimation of unit weight)	3, 6, 28
	8	MEP planning and MEP space requirement review	1, 3, 4
Design Development	9	Develop and modify the schematic design	3, 10, 11, 13, 15, 16
	10	Determine interior and exterior materials	9
	11	Determine structural system design	6, 7, 9, 12
	12	Structural design analysis and structural calculation documentation	11, 35
	13	Draft the locations and sizes of structural components	9, 11, 12
	14	Bar arrangement drawing documentation	13
	15	Determine MEP system	1, 8, 9
	16	Reviewing MEP and structural component interference	9, 13, 15
Construction	17	Prepare construction document of the	9, 18, 20, 21

Documentation		design	
	18	Structural and MEP system adjustment and documentation	11, 15, 17, 21
	19	Architectural details, specifications, and structural calculation documentation and incorporate subcontractor documentation	17, 18, 20
	20	Principal structural parts finishing and propriety review	21
	21	Check the errors and omissions in documentation and constructability review	17, 20
Manufacturing	22	Determine and review the work activities for unit production in factory (determine factory work)	1, 17, 27, 28, 29
	23	Prepare shop drawings and check interference in unit production	22
	24	Prepare unit production line design	23
	25	Prepare manufacturing tolerance management plan	17, 22, 23, 26
	26	Prepare quality management plan	22, 25
Transportation	27	Prepare management plan for reducing deformation and damage	1, 22
	28	Review the Road Traffic Act regulation (weight and size of unit)	1
On-site Work	29	Determine the on-site work activities	22
	30	Select tower crane location	1, 2, 28
	31	Select tower crane specification	17, 22, 30
	32	Prepare shop drawings and check for interference	29, 33
	33	Review constructability for on-site work	29, 32
	34	Prepare on-site work tolerance management plan	29
	35	Prepare deformation management plan in unit lifting process	12
	36	Prepare unit proofing plan to reduce damage from weather conditions	17, 22

For the rearrangement, the DSM of the modular construction planning process is developed based on the information flow relationship in Table 3-4. Figure 3-4 shows the DSM. The marks above the diagonal represent the reverse information flow causing feedback. The optimization objective of the DSM is to move as many marks as possible to below the diagonal (Oloufa et al., 2004). A partitioning algorithm is used as the optimization algorithm. The reverse information flow and feedback processes between activities can be reduced by using the algorithm. Figure 3-5 shows the rearranged activities and information flow in the DSM.

The activities with strong interdependencies are grouped. Although the feedback process is reduced by the optimization, there are still feedback processes. The activity groups A, B, C, and D require information flow management because the feedback processes are concentrated within the groups. As a result of quantitative optimization, the reverse information flow is reduced from 23 to 18 after rearrangement of the activity order. For example, the Road Traffic Act regulation review in the transportation planning phase is reallocated to the SD phase. The reverse information flow of the activity is thus reduced from 4 to 0. This reduced reverse flow means that the regulation review affects other activities in the process. By allocating the regulation review to the early design phase, engineering rework in the design and planning phase can be reduced. Given that the results of the SD phase affect the following activities, reallocation in the early phase implies that the potential rework in the following phase can also be reduced.

Element Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Site analysis	1	1																																			
Site layout planning	2	1	2																										1		1						
Establish design direction in terms of plan, section, and elevation	3		1	3	1																								1								
Building core planning	4			1	4																																
Explore interior and exterior material	5			1		5																															
Reviewing the strength of material, structural design criteria, design load	6	1		1			6																														
Reviewing alternatives of structural system design such as size of component (rough estimation of unit weight)	7			1			1	7																					1								
MEP planning and MEP space requirement review	8	1		1	1				8																												
Develop and modify the schematic design	9			1						9	1	1		1		1	1																				
Determine interior and exterior material	10									1	10																										
Determine structural system design	11						1	1		1		11	1																								
Structural design analysis and structural calculation documentation	12											1	12																							1	
Draft the location and size of structural component	13									1		1	1	13																							
Bar arrangement drawing documentation	14													1	14																						
Determine MEP system	15	1							1	1						15																					
Reviewing MEP and structural component interference	16									1				1		1	16																				
Prepare construction document of the design	17									1								17	1		1	1															
Structural and MEP system adjustment and documentation	18											1				1		1	18			1															
Architectural detail, specifications, structural calculation documentation and incorporate subcontractor's documentation	19																	1	1	19	1																
Principal structural parts finishing propriety review	20																				20	1															
Check the errors and omissions in documentation and constructability review	21																	1			1	21															
Determine and review the work activities for unit production in factory (Determine factory work)	22	1																1					22					1	1	1							
Prepare shop drawing and check the interference for unit production	23																						1	23													
Prepare unit production line design	24																							1	24												
Prepare manufacturing tolerance management plan	25																	1					1	1		25	1										
Prepare quality management plan	26																						1			1	26										
Prepare management Plan for reducing deformation and damage	27	1																					1					27									
Review the Road Traffic Act regulation (weight and size of unit)	28	1																											28								
Determine the on-site work activities	29																						1							29							
Select tower crane location	30	1	1																										1		30						
Select tower crane specification	31																	1					1								1	31					
Prepare shop drawing and check the interference	32																													1			32	1			
Review constructability for on-site work	33																													1			1	33			
Prepare on-site work tolerance management plan	34																													1					34		
Prepare deformation management plan in unit lifting process	35												1																							35	
Prepare unit proof plan to reduce the damage from weather condition	36																	1					1														36

Figure 3-4. Information flow identification using DSM.

Element Name		1	28	30	2	3	4	5	6	7	8	9	10	11	12	13	15	16	35	14	17	18	20	21	19	22	27	29	23	24	25	26	31	32	33	34	36
Site analysis	1	1																																			
Review the Road Traffic Act regulation (weight and size of unit)	28	1	28																																		
Select tower crane location	30	1	1	30	1																																
Site layout planning	2	1	1	1	2																																
Establish design direction in terms of plan, section, and elevation	3		1		1	3	1																														
Building core planning	4					1	4																														
Explore interior and exterior material	5							5																													
Reviewing the strength of material, structural design criteria, design load	6	1				1			6																												
Reviewing alternatives of structural system design such as size of component (rough estimation of unit weight)	7		1			1			1	7																											
MEP planning and MEP space requirement review	8	1				1	1				8																										
Develop and modify the schematic design	9					1						9	1	1		1	1	1																			
Determine interior and exterior material	10											1	10																								
Determine structural system design	11								1	1		1		11	1																						
Structural design analysis and structural calculation documentation	12													1	12				1																		
Draft the location and size of structural component	13											1		1	1	13																					
Determine MEP system	15	1									1	1					15																				
Reviewing MEP and structural component interference	16											1				1	1	16																			
Prepare deformation management plan in unit lifting process	35														1				35																		
Bar arrangement drawing documentation	14															1				14																	
Prepare construction document of the design	17											1									17	1	1	1													
Structural and MEP system adjustment and documentation	18													1			1				1	18		1													
Principal structural parts finishing propriety review	20																						20	1													
Check the errors and omissions in documentation and constructability review	21																				1		1	21													
Architectural detail, specifications, structural calculation documentation and incorporate subcontractor's documentation	19																				1	1	1		19												
Determine and review the work activities for unit production in factory (Determine factory work)	22	1	1																		1					22	1	1									
Prepare management Plan for reducing deformation and damage	27	1																								1	27										
Determine the on-site work activities	29																									1		29									
Prepare shop drawing and check the interference for unit production	23																									1			23								
Prepare unit production line design	24																												1	24							
Prepare manufacturing tolerance management plan	25																				1					1			1		25	1					
Prepare quality management plan	26																									1					1	26					
Select tower crane specification	31			1																	1					1							31				
Prepare shop drawing and check the interference	32																											1						32	1		
Review constructability for on-site work	33																											1						1	33		
Prepare on-site work tolerance management plan	34																											1								34	
Prepare unit proof plan to reduce the damage from weather condition	36																				1					1											36

A B C D

Figure 3-5. Rearranged activities by optimization.

3.4 Integrated Planning Process for Modular Construction

3.4.1 Schematic Design Phase

By the DSM optimization, activities in the planning and design phase are rearranged with a focus on reducing rework. By the rearrangement, an integrated design and planning process is suggested. In the schematic design phase, the Road Traffic Act regulation review in transportation planning and tower crane location selection in on-site work planning are included. When developing building design alternatives, it is necessary for the building design to adhere to the Road Traffic Act regulations. If the design does not meet the regulations, rework in the design phase occurs to rectify the building design because modular units must be transported to on-site.

In the schematic design phase, Figure 3-5 shows the feedback process in activity group A between the site layout planning and tower crane location selection. In the planning phase of on-site work, the selection and positioning of tower cranes on the construction site are essential because heavy units must be lifted (Al-Hussein et al., 2001; Han et al., 2012; Han et al., 2014). In the tower crane operational plan, the capacity is estimated based on a combination of the maximum distance that the tower crane must reach and the weight of the material. By reducing the maximum distance, the tower crane operational cost can be reduced. For example, in the schematic design phase, after estimating the weight of the unit roughly, tower crane location alternatives are suggested considering alternative site layout planning. Then, the tower crane capacity can be estimated according the combination of alternatives. If a tower crane with the required capacity cannot be obtained from a crane rental company or if the operational cost is uneconomical, the weight of unit, location of the crane, or site layout plan are modified to meet the project objectives. After the design process with the consideration of regulation review and tower crane operation is completed, in the schematic design phase, a building design is selected among design alternatives by considering the feasibility and project objectives.

3.4.2 Design Development Phase

In the design development phase, the selected design from the schematic design phase is developed, and the building systems, such as architectural, structural, and MEP systems, are determined. Activity group B shows that the feedback process between activities to determine building systems and information flow management is required to facilitate information interchange between project participants. In this phase, MEP and structural design are developed, and the interference between these activities often occurs. Therefore, to reduce rework caused by interference, an accurate design review between activities is required, which means there will be feedback in this design process. In these phases, on-site work planning is included to prevent transformation of units. When lifting a unit on-site, transformation caused by self-load of the unit can occur. By this transformation, the quality of unit can be affected, which can cause difficulty in the on-site unit assembly phase. To prevent this transformation, a balance beam can be used, but transformation may still occur for heavy units. There is also an approved transformation range in the assembly phase. However, when the transformation exceeds the approved range, rework to revise the transformation should be conducted. Therefore, the higher the quality and precision standards of the modular units result in common problems when they are fitted onto less precise components onsite or when the precision of the unit is decreased (Blismas and Wakefield, 2009). Therefore, when selecting the structural system and conducting structural analysis of units, it is necessary to plan for preventing transformations induced by self-load.

3.4.3 Construction Documentation Phase

In the construction documentation phase, the results of the design development phase are considered and details are determined. Then, construction documents, such as drawings, for details and specification are prepared for manufacturing and on-site work. In this phase, the participants in the design planning phase crosscheck the design documents to rectify errors and omissions. The design document is used to prepare shop drawings for unit production and on-site work. The shop drawings are related to project quality. Hence, interference between components or activities should be checked and rectified. Activity group C shows the feedback process in this phase, and consideration of constructability, information interchange, and rectification should be facilitated between participants because the results of this phase are related to manufacturing and on-site work.

3.4.4 Manufacturing, Transportation, and On-site Work Planning Phase

In this phase, manufacturing, transportation, and on-site work planning, which are not included in the previous design phases, are established based on the results of the construction documentation phase. To improve the efficiency of modular construction, the most activities possible must be conducted in the manufacturing process. However, in a modular construction project, after the manufacturing process, units are transported to the construction site, and it is necessary for the work planning to be established based on the site environment and road conditions. Therefore, the work activities conducted in the manufacturing process are selected considering unit transformation in transportation, damage to units, and site environment. Then, the remaining activities to complete the project are conducted on-site. Given that the work proportions are determined depending on the project characteristics, the proportions have flexibility. This work activity distribution is shown by activity group D in Figure 3-5.

In activity group D, manufacturing, transportation, and on-site work planning are cross-checked and rectified by the participants. Therefore, there are feedback processes between activities, and cooperation is required between participants. Moreover, in addition to work planning related to rework, other work planning for activities is included in this phase. Therefore, information flow management is required to facilitate development of the work planning because the work planning of this phase is directly related to the performance of the modular project.

The integrated planning process can contribute to reducing rework in modular construction projects by integrating the rework mitigation plans and the work planning. To employ this planning process, modular construction must be considered in the early project phase by the project client or in the early design stage. Then, to facilitate the process and to include project participants in the early design phase, project delivery methods, such as IPD, should also be considered (Smith, 2011).

However, there are hindrances to choosing the modular construction, such as early design freeze, limited experience, short overall project timescale, and unavailability of advice in the early phase (Blismas et al., 2005). Moreover, follow-on projects cannot use the same processes of previous projects, which is a constraint caused by a lack of experience and knowledge (Blismas et al., 2005). To overcome this, a standardized modular construction process is required, and the proposed design process can be used to overcome the constraints and reduce rework in modular construction.

3.5 Summary

Modular construction has benefits, such as low cost, short period, and high quality, which are attributed to conducting work activities in a factory. However, in modular projects, rework occurs as in stick-built construction, and this rework affects modular project performance in terms of cost, time, and quality. Typically, a significant proportion of rework is caused by errors made during the design process. To reduce rework, a comprehensive planning process is required, including designing and unit production and on-site work planning to reduce rework.

In this chapter, the integrated design and planning process is proposed, including mitigation plans to reduce rework in manufacturing and on-site work. By using the proposed design process, engineering rework in the planning phase and field rework in the manufacturing and on-site work phases can be reduced. By optimization of the DSM for a modular construction planning process, the feedback process between design and work planning activities is reduced, and information flow complexity can be reduced.

However, this research has limitations in that 1) to validate this research, application of the planning process to modular projects is required, 2) the work planning is limited to some cases in the daily report, and 3) in the planning process, detailed information of participants to conduct each activity is not included; thus, the process cannot suggest information of participants who should be included to conduct each work in the planning process. To overcome these limitations, a case study including more cases of rework and quantitative evaluation will be conducted in future research.

Chapter 4. Multi-Objective Optimization for Modular Unit Production Line Design

4.1 Unit Production and Multi-Objective Optimization

In the previous chapter, a method to determine the proportions of off-site work and on-site work was proposed. In this chapter, a method to schedule unit production is introduced. As described in the previous chapter, a significant proportion of the work in a project is conducted in a factory, and the produced hexahedral units are transported and assembled on-site (Mullens, 2011). Therefore, the efficiency of the unit production line is directly related to the project performance. Moreover, unit production scheduling requires various production line designs due to flexibility of modular project schedules. Therefore, a production line design method that can cope with various schedule alternatives with improved productivity is required. However, the production process is still primitive compared to other manufacturing industries (Banerjee et al., 2006; Lee et al., 2017).

In the manufacturing industry, to improve the efficiency of production lines, JSS, flow shop scheduling (FSS), and flexible JSS (FJSS) have been used (Al-Bazi and Dawood, 2010; Anvari et al., 2016; Asefi et al., 2014; Han et al., 2014; Ko and Wang, 2011; Liu et al., 2016; Wang et al., 2017).

Production line scheduling in the manufacturing industry is a well-known problem and is defined as an NP-hard combinatorial problem (Anvari et al., 2016; Murata et al., 1996). To minimize the makespan, required resources, and idle time, the schedule is optimized by sequencing the job operations. Then, assignment of each operation to resources, such as machinery and the workforce, are optimized based on the assumption that one machine is assigned to each stage, and no more than one job can be processed at a time (Chen and Tiong, 2018; Chen et al., 2018; Dudek et al., 1992; Liu et al., 2016; Murata et al., 1996).

In all scheduling methods except FSS, space is required to store the components until the machine completes the previous job. This continuous type of modular unit production line is based on the flow shop production line. Therefore, storage space for idle time is not required. However, there can be a scenario where multiple activities are conducted at one station or at multiple stations to reduce the required space for the production line due to heavy units (Banerjee et al., 2006; Lee et al., 2017; Mullens, 2011). Thus, the unit production line is designed by combining activities. The combinations of stations changes according to the production line variables, such as cycle time and resources allocated to works. Each change represents an alternative production line design, and a large number of alternatives can be generated according to the variables. Therefore, although the variables modified in optimization process are different, optimization of the unit production line can be defined as a combinatorial problem just as production line scheduling in other manufacturing industries.

To improve the unit production line, the goals of the manufacturing industry, such as minimization of required resources, idle time, cost, and makespan, have also been considered as optimization objectives, and one of the objectives is selected according to the optimization purpose (Al-Bazi and Dawood, 2010; Arif et al., 2002; Banerjee et al., 2006; Chen and Tiong, 2018; Chen et al., 2018; Lee et al., 2017). However, in terms of production line optimization, the project manager is faced with a multi-objective optimization (MOO) problem. For example, in the production line process, there is a trade-off relationship between cost and time. When more workers are allocated, the production rate will increase, but the cost will also increase, and when less workers are allocated, the production rate and cost will decrease (Al-Bazi and Dawood, 2010; Dawood et al., 2007). However, it is difficult to choose the best solution as a single optimization result considering this trade-off. Thus, a multi-objective solution is required (Murata et al., 1996). Moreover, the project manager is required to cope with various production schedule alternatives without loss of the optimization objective.

To deal with this challenge, this dissertation proposes a MOO model for a continuous modular unit production line (MOMUPL). The main drivers of using the modular construction method are short project duration and improved labor productivity; hence, the maximization of production amount and minimization of allocated workers are selected as optimization objectives (Blismas and Wakefield, 2009). The expected contributions of this research are that 1) the difference between unit production line design and the other production line scheduling, such as JSS, FJSS, and FSS, is explained, 2) by using the proposed MOMUPL, the combinatorial MOO problem for the unit production line can be solved, 3) optimized production line solutions are suggested, and 4) by using the extended variation of solutions, the project manager can schedule a modular project with flexibility. To achieve the objectives of this research, the differences between unit production line and other production lines are identified through a literature review. Then, to solve the MOO problem, MOMUPL is developed based on the genetic algorithm (GA). To validate MOMUPL, a case study is conducted, and production line design is suggested. Finally, the optimization results are discussed.

4.2 Multi-Objective Production Line Design

4.2.1 Production Line Scheduling in Manufacturing Industry

The JSS and FSS problems are well known problems in the manufacturing industry (Anvari et al., 2016; Murata et al., 1996). The objectives of minimizing the makespan, resource, and cost are often employed as scheduling optimization goals (Al-Bazi and Dawood, 2010; Murata et al., 1996). A schedule presents which work must be performed, which resources are required, and the time frame in which to organize the works in sequence (Anvari et al., 2016). To achieve the optimization goal, many studies have been conducted (Al-Bazi and Dawood, 2010; Anvari et al., 2016; Asefi et al., 2014; Han et al., 2014; Ko and Wang, 2011; Liu et al., 2016; Wang et al., 2017). In JSS, works are allocated to predefined resources, which are shared, and the sequence of works is determined. Therefore, the work sequence is optimized to achieve the objective goal. In FSS, the resources are allocated in a row according to a predefined sequence, and the works are conducted through the line. In FSS, although the order of resource use for each work is determined, the work sequence must be arranged because each work requires different resources and duration. If a resource is occupied by previous work, the following work should wait until the previous is complete. Therefore, idle time may occur, and to minimize this idle time, the work sequence is arranged using an optimization process. In the JSS, space is required to store the components during idle time (Chen et al., 2018). The idle time and storage space are related to the optimization objectives. Hence, the sequence and order of resource use are arranged to minimize them. The arrangement can be determined as a combinatorial problem of work sequence and order of resource usage. Thus, the production line schedule is defined as NP-complete problem (Anvari et al., 2016).

4.2.2 Modular Unit Production Line Design

The continuous type of modular unit production line is based on flow shop production, and units are produced on the line by going through each work activity station (Mullens, 2011). The units on the line progress to the next station after each cycle time elapses. By using the continuous type, storage space constraints can be alleviated for idle time. In the unit production line, however, work activities are grouped and allocated to stations to reduce the required space for the production line due to heavy units (Banerjee et al., 2006; Lee et al., 2017; Mullens, 2011). The work activities are conducted in accordance with a predefined sequence, but the combinations of activities vary according to variables, such as cycle time and resource allocation (Nasereddin et al., 2007). The combined activities represent stations on the line. The variables are adjusted to achieve the optimization objectives. Therefore, in terms of the combinatorial problem, the unit production line is similar to those of JSS and FSS. However, there are differences between unit production line design and flow shop production line scheduling. For example, JSS and FSS are combinatorial problems of work sequences, but the unit production line design is a combinatorial problem of allocated resources and cycle time. Figure 4-1 shows examples of unit production line designs according to cycle time and labor allocation. Each design has different properties, such as idle time, allocated workers, and number of stations. Moreover, the works at each station are almost all construction works conducted by workers; hence, the work duration varies according to the number of workers. The other production line is scheduled based on the assumption that the work duration is predefined, which is the other difference in scheduling.

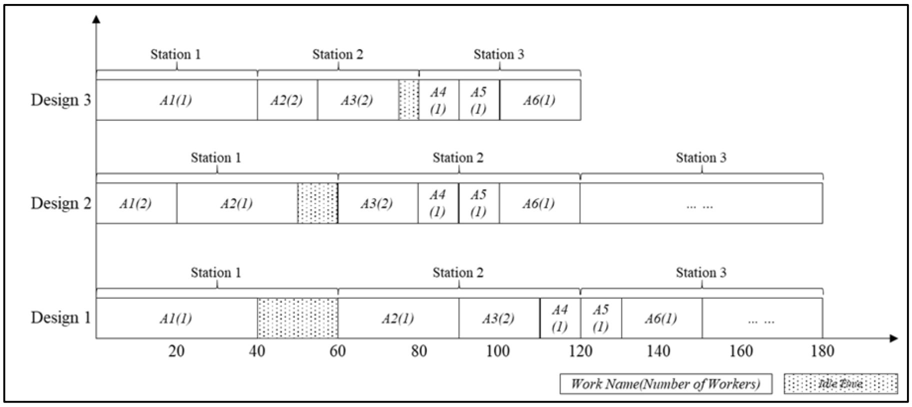


Figure 4-1. Examples of modular unit production line design.

4.2.3 Multi-Objective Optimization for Unit Production Line

To improve the modular unit production line, many studies have been conducted. Lee et al. (2017) suggested a manufacturing process for modular units to reduce the complexity of the assembly line based on the precedence relationships among activities. Through the suggested process, activities are rearranged and grouped to prevent bottlenecks. To improve work continuity on the production line, Chen and Tiong (2018) developed a model to suggest the facility layout of a manufacturing system for prefabricated bathroom units (PBUs) considering the space constraint caused by heavy PBUs. Then, Chen et al. (2018) optimized the production line schedule for PBUs considering the space constraint caused by settling the unit and storing it for idle time. In that research, the production start time was controlled to prevent bottlenecks caused by the space constraint. Mehrotra et al. (2005) developed a systematic approach to the unit production line design based on a qualitative method. The shape of assembly line design can be suggested based on the space requirements and relationship between activities to maintain work continuity without influence caused by the space constraint. Based on the results of Mehrotra et al. (2005), Banerjee et al. (2006) suggested a process for modular unit assembly layout design with a focus on the material flow. In that research, the workflow of the production was improved by reducing the distance of material movement, which in turn reduced the cost of material movement. These previous studies improved work continuity by reducing bottlenecks or idling time caused by other resource constraints.

In the unit production line, work continuity can be maintained by planning the production rate of each work (Arif et al., 2002; Carr and Meyer, 1974; Cho et al., 2013; El-Rayes and Moselhi, 1998; El-Rayes and Moselhi, 2001; Ioannou and Yang, 2016; Ipsilandis, 2006; Nassar, 2011; Reda, 1990). The production rate is adjusted by crew allocation; hence, crew allocation is considered an important factor in unit production line design. Arif et al. (2002) developed a system for labor estimation and a planning system for modular production lines and suggested a concept of collecting real-time labor data on the assembly line. The research suggested a tool that has a valuable impact on labor allocation, which is considered a major factor in assembly line design. Al-Bazi and Dawood (2010) developed a system to suggest a precast concrete manufacturing schedule based on crew allocation and optimized the crew allocation plan considering crew utilization rate. By the suggested schedule, labor cost could be reduced and work continuity could be improved by reducing idling time.

Previous research has focused on increasing production amount or reducing cost. However, the manufacturing industry must reduce cost while maintaining the production performance or increase production performance with minimum cost (Anvari et al., 2016; Liu et al., 2016; Murata et al., 1996).

Ko and Wang (2011) developed a multi-objective GA model to schedule heavy precast concrete production to minimize duration and cost. The cost includes inventory cost and cost of tardiness and earliness for large volumes of precast concrete. Anvari et al. (2016) developed an MOO model to minimize time and cost considering the whole precast construction project process, including manufacturing, transportation, and assembly. Although the optimization model for precast concrete production deals with heavy components, the production lines are similar to those for job shops. Therefore, there is a limitation in applying a modular unit production line to combined work activity. Hence, this dissertation proposes a multi-objective optimization model for continuous modular unit production line (MOMUPL). Given that the major drivers of utilization of modular construction are short construction duration and improved labor productivity, the maximization of unit production and minimization of allocated workers are selected as optimization objectives of the model (Blismas and Wakefield, 2009).

4.2.4 Optimization Methodology

Modular production line design is a combinatorial optimization problem just as JSS and FSS, which are NP-complete problems (Al-Bazi and Dawood, 2010; Anvari et al., 2016; Liu et al., 2016). In the optimization process, a great number of solutions are compared, and then optimization results are suggested. Therefore, such problems are computational demanding to solve (Anvari et al., 2016). Mathematical programming, such as mixed integer linear programming (MILP), can determine an exact optimal solution but requires significant computation time (Anvari et al., 2016). Therefore, to reduce computation time, meta-heuristic algorithms have been used. Evolutionary algorithms, which belong to the meta-heuristic algorithms, have been used to solve nonlinear complex optimization problems, and they consider a vast number of possible solutions to provide optimal results (Anvari et al., 2016; Rahnamayan et al., 2007). The GA is an evolutionary algorithm and consists of an initial population, genetic operations, and objective functions (Anvari et al., 2016).

MOMUPL in this research is a GA-based MOO model. In MOO, to select solutions in the population for a new generation, Murata et al. (1996) suggested a method of integrating the multi-objective into a single objective using variable weight for each objective. By using this integrated objective, solutions are selected for the new generation just as in single objective optimization. However, the major drawback of integration into a single objective is that the weights are hardly given properly when the objective functions are measured at different scales (Wang et al., 2017). To overcome this drawback, the non-dominated sorting genetic algorithm II (NSGA-II) suggested by Deb et al. (2002), which is a multi-objective evolutionary algorithm (MOEA) based on the GA, has been used to solve multi-objective optimization problems (Asefi et al., 2014). The methods provide a set of optimal solutions, which are known as Pareto-optimal solutions or non-dominated solutions on Pareto-fronts, instead of a single optimal solution. Therefore, it is necessary to sort the optimal solutions to rank and allocate the solutions to Pareto-fronts. Figure 4-2 illustrates the sorting method in NSGA-II. Through the crossover and mutation operators, the offspring population is generated, and the parent and offspring populations are combined. The size of the combined population is 2N, and the population is sorted to reduce the population size to N using the non-dominated sorting and crowding distance sorting methods, which are used to maintain diversity in the optimal results. The solutions on the same Pareto-front are not superior to the others, but the solutions on front 1 are superior to all solutions on other fronts (Deb et al., 2002). Due to the simplicity, good convergence, and diversity of NSGA-II, it has proved effective to design the optimal production line by reducing cost and duration (Deb et al., 2002; Han et al., 2014; Liu et al., 2016). Therefore, in MOMUPL, the sorting method of NSGA-II is employed to solve the multi-objective problem.

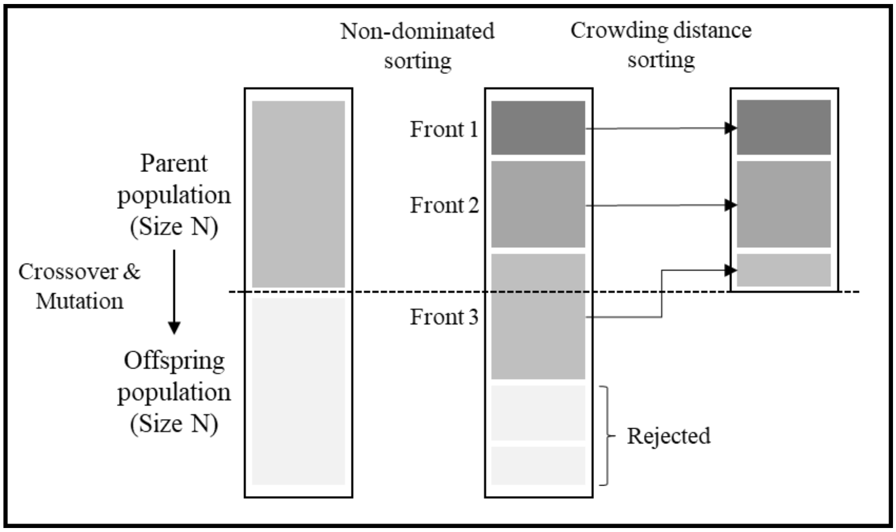


Figure 4-2. Solution sorting procedure in NSGA-II (Deb et al., 2002).

4.3 Multi-Objective Optimization Model for Continuous Modular Unit Production Line (MOMUPL) Development

4.3.1 Problem Description

In the modular unit production line, a number of different works are conducted and are grouped to be allocated to a station. In the line, most of the works consist of construction works, and labor is a major resource for these works. Therefore, the duration of each work changes according to the number of workers. At a given station, the allocated works are conducted in a cyclic manner, and the cycle time is a major variable in line design. When the number of workers for each activity and cycle time are determined, one design solution is generated. Therefore, the optimization problem can be defined as a combinatorial problem of the number of workers and cycle time.

Designing a unit production line requires the following specific information of works as input data: 1) a list of works, 2) sequence of works, 3) types of workers for each activity, 4) man-hours of each activity, 5) minimum number of workers required to conduct each activity smoothly, and 6) maximum number of workers for each activity to be inputted without workspace interference. Using this information, the variables, such as the number of workers and cycle time, are determined, and combinations are generated according to the change of variables. To optimize the unit production line, the following assumptions are made: 1) only labor resources affect the work duration, 2) the works on each station should be completed in the cycle time, 3) the duration required to move a unit to the next station is not considered, 4) the workers conduct only their assigned work and multi-skilled labor is not considered, 5) the number of stations is not limited, 6) preemption of works is not considered, and 7) if there are the works on a station that require the same type of workers, the number of workers required to conduct one work are allocated to reduce the total number of workers. For example, if there are 3 works on the same station (A_i, A_{i+1}, and A_{i+2}) that require the same type of workers, the workers conduct A_i, A_{i+1}, and A_{i+2} sequentially; hence, the number of workers required to conduct A_{i+1} and A_{i+2} can be reduced.

4.3.2 Problem Formulation

A unit production line consists of a set of works, which is represented here as A_1, A_2, A_3, ..., and A_i. The number of allocated workers to A_i is represented as W_i. The duration of A_i is represented as at_i, which can be calculated using the man-hours of A_i, represented as AT_i. When designing a production line, the cycle time is determined, and a t minute cycle time is represented as CT_t. By calculating at_i and CT_t, works are grouped and allocated to stations. Stations on the production line are represented as S_1, S_2, S_3, ..., and S_k. To allocate work A_i to station S_k, the idle time of the station and duration of work are compared. If the idle time, which is represented by LCT_k, is longer than at_i, A_i is allocated to S_k. Otherwise, the next station S_{k+1} is generated. The comparison procedure is conducted iteratively to allocate all works to stations. When the last work is allocated, one single solution for population in the optimization process is provided. As mentioned in the previous section, the objective functions are minimization of the total number of workers and maximization of the number of produced units. The total number of workers *TW* can be estimated by adding the allocated number of workers to each activity, and the total produced unit *TP* can be estimated by using cycle time and the number of stations. This unit production line optimization is subject to a set of constraints. Constraint (1) determines the bounds of W_i, (2) determines the limitations of CT_t, and (3) determines whether A_{i+1} can be allocated to S_k, and if LCT_k is longer than at_{i+1}, A_{i+1} is allocated. Table 4-1 lists the notations and constraints in the optimization process.

Table 4-1. Notations and constraints for MOMUPL.

Indices	
n	*total number of works*
i	*work index, where $i = \{1, 2, 3, \ldots n\}$*
m	*total number of stations*
k	*station index, where $k = \{1,2,3, \ldots m\}$*
l	*total number of works allocated to S_k*
Sets	
A	*set of works $A = \{ A_1, A_2, A_3, \ldots A_i \}$*
S	*set of stations $S = \{ S_1, S_2, S_3, \ldots S_k \}$*
AT_i	*man-hours of A_i*
$MinW_i$	*minimum number of workers required to conduct A_i*
$MaxW_i$	*maximum number of workers that can be allocated to A_i*
Parameters	
TD_t	*t minute total production time for optimization experiment (integer number)*
Variables	
W_i	*number of workers allocated to A_i*
CT_t	*t minute cycle time (integer number)*
at_i	*work duration of A_i*, where $at_i = \frac{AT_i}{W_i}$
ST_k	*If the previous activity is at_{i-1} on S_{k-1} and the number of allocated works is l, this is the*

	duration for conducting the total allocated work to S_k*, where* $ST_k = \sum_{x=i}^{n+l-1} at_x$ *(if* l *is 0,* ST_k *is also 0)*
LCT_k	*idle duration of* S_k*,* $LCT_k = CT_t - ST_k$
TW	*total number of workers on production line, where* $$TW = \sum_{x=1}^{n} W_x$$
TP	*total produced units for* TD_t *is the quotient of* $TD_t - (CT_t \times m) / CT_t$

Objective

Minimization of TW

Maximization of TP

Subject to

(1)	$MinW_i \leq W_i \leq MaxW_i$
(2)	*maximum value of* $at_i \leq CT_t$
(3)	$at_{i+1} \leq LCT_k$

4.3.3 GA for MOMUPL

In the GA optimization, a chromosome represents a single solution of the unit production line, and a set of chromosomes is randomly generated to comprise an initial population of size N. Then, using a genetic operator, such as mutation or crossover, an offspring population of size N is generated. The crucial elements of GA optimization are chromosome definition, design of genetic operators, and deciding which chromosomes are selected in each population for applying genetic operators (Anvari et al., 2016). Figure 4-3 shows the encoding schema of MOMUPL. In this research, the variables affecting unit production line design are W_i and CT_t. When the variables are determined, the production line performance indicators, such as TW and TP, can be estimated. Therefore, a chromosome in MOMUPL consists of two parts: 1) the first part is a representation of CT_t using a binary system, and 2) the second part is a representation of the works on the production line. In the chromosome representing the second part, each gene represents a work A_i, and the value of a gene indicates a W_i. Therefore, the length of a chromosome represents the total number of works n.

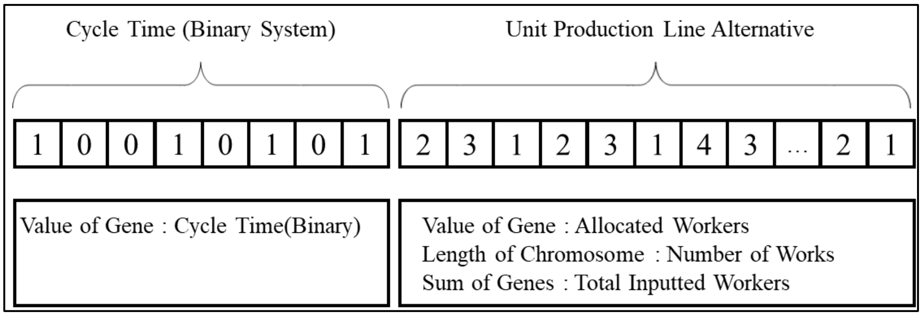


Figure 4-3. Encoding schema of MOMUPL.

After generating the initial population, to generate an offspring population, crossover and mutation operators are used. The crossover operator in this research is a one-cut-point crossover operator, and the crossover point is randomly determined, as shown in Figure 4-4. The mutation operator produces random changes in genes. MOMUPL adopts two mutation strategies to produce offspring, as shown in Figure 4-5. In the first strategy, one gene is selected from each part of a chromosome, and the values of two genes are randomly changed, as shown in Figure 4-5(a). In the other strategy, each gene is randomly selected to change the value or not. In this strategy, a gene or genes are selected and its value changes randomly, as shown in Figure 4-5(b). The first mutation strategy is adopted to improve the results of searching in the local area. The other one is adopted to maintain diversity in the population.

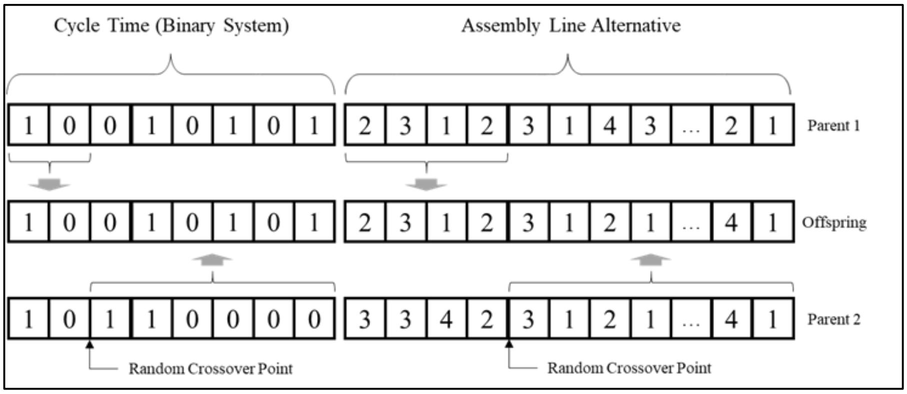


Figure 4-4. Crossover operator of MOMUPL.

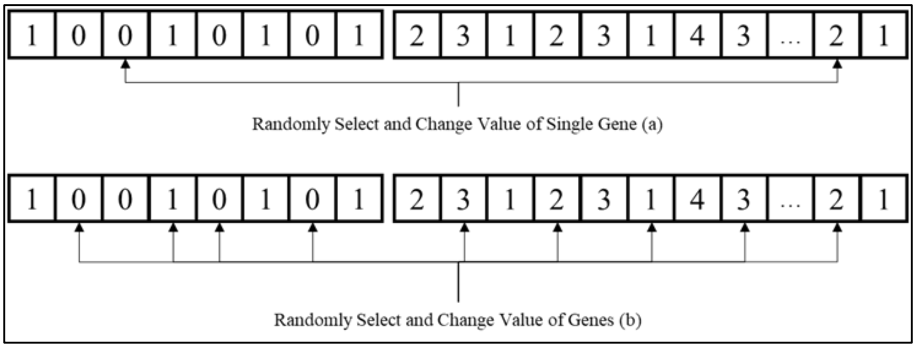


Figure 4-5. Mutation operator of MOMUPL.

After the offspring population is generated, the initial and offspring populations are combined. Then, using NSGA-II, the size of the population is reduced from 2N to N. By using the information of each chromosome, the fitness is calculated based on the objectives, and the chromosomes are ranked using NSGA-II, as shown in Figure 4-1. In the NSGA-II, the solutions belonging to the best non-dominated set front 1 are the best solutions in the combined population. If the size of front 1 is smaller than N, all solutions in front 1 are chosen for the population of the new generation. The remaining solutions of the population in the new generation are chosen from the subsequent non-dominated fronts in order of their ranking. Thus, solutions from front 2 are chosen, and this procedure is continued until no more fronts can be included. In Figure 4-1, the number of solutions from front 1 to front 3 is larger than N. To make the population size exactly N, the solutions in the last front are sorted using the crowding distance comparison operator, as shown in Figure 4-6. The crowding distance value indicates how near a solution of the front is to other solutions. By using the crowding distance comparison operator, all solutions from last front are ranked according to their crowding distance values, and to maintain the diversity in the population, the solutions with larger values are chosen to fill the new population (Deb et al., 2002). By conducting this GA procedure iteratively, the optimization results are improved.

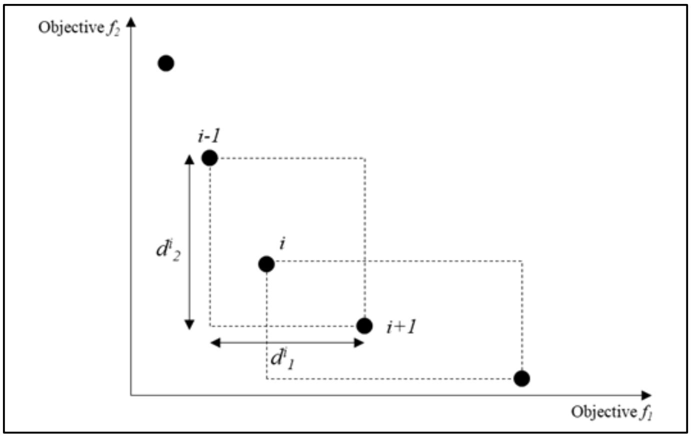


Figure 4-6. Diagram of crowding distance.

4.4 Case Studies

To suggest modular unit production line solutions considering multi-objective, a case study was conducted. In this case study, 45 works were allocated to a production line, and each activity was given different properties, such as ID, type of required workers, man-hours of each work, maximum or minimum number of workers, and work inside or outside of a unit. Table 4-2 shows an example of work information, and all activity information is presented in the appendices. Table 4-3 lists the optimization experiment parameters in this case study. This optimization experiment starts with 100 chromosomes, and by the iterative evolutionary process, the result is improved. After 300 iterations, the optimization experiment is finished, and results are provided. 200 solutions are assigned to 15 fronts. Figure 4-7 shows the optimized solutions from front 1. The number of produced units represents the number of units that are produced over 10,000 minutes.

Table 4-2. Example of work information.

ID	Work Name	Man-hours	Type of Worker	Minimum Number of Workers	Location	Maximum Number of Workers
1	Wall Stud Installation	40	Sheet Steel Worker	2	Inside	4
2	Insulator to Steel Frame Installation	30	Construction Labor	1	Outside	4
3	Door and Window Frame (Short Side)	40	Window Framer	2	Outside	4
4	Install Pipe Shaft Frame	10	Metal Worker	1	Outside	4
5	Corner Floor Concrete Pouring	10	Construction Labor	1	Inside	4
6	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	20	Joiner	2	Inside	4

Table 4-3. Optimization experiment parameters.

Optimization Experiment Parameters	
Initial population size	100
Termination condition	300 iterations
Simulation time	10,000 minutes
Crossover rate	0.5
Mutation rate for single gene selection	0.3
Mutation rate for multi-gene selection	0.2

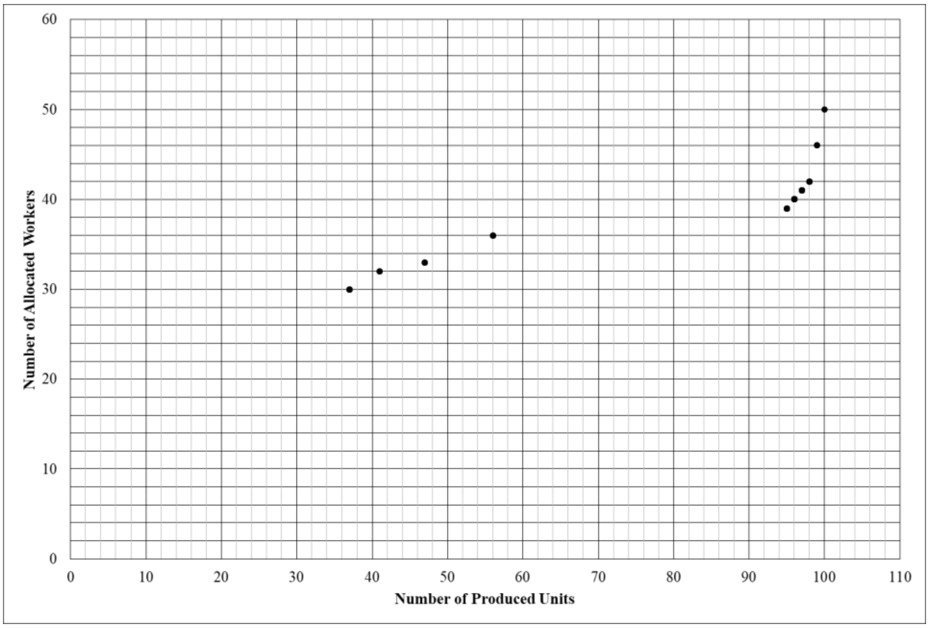


Figure 4-7. Optimized production line solutions in Pareto front.

In front 1, 80 solutions are suggested. The results show that the total number of produced units ranges from 37 to 100, and the number of workers ranges from 30 to 50. However, in Figure 4-7, only 11 solutions can be seen, which means there are the solutions with the same results. Although the solutions have overlapping results, each solution has a unique production line design, such as different cycle time, idle time, work allocation, and number of stations. Therefore, when designing a production line, a decision maker can choose the solution with consideration of the project's characteristics or other conditions. Table 4-4 lists the information of solutions in front 1. Table 4-5 shows an example diagram of an optimized production line.

Table 4-4. Information on solutions on Pareto front 1.

ID	Units	Workers	Cycle Time	Stations	ID	Units	Workers	Cycle Time	Stations
1	37	30	240	5	41	97	41	91	13
2	37	30	240	5	42	96	40	92	13
3	37	30	241	5	43	98	42	91	12
4	97	41	92	12	44	95	39	92	14
5	37	30	240	5	45	96	40	92	13
6	97	41	92	12	46	98	42	91	12
7	97	41	92	12	47	96	40	92	13
8	97	41	92	12	48	96	40	92	13
9	97	41	92	12	49	98	42	91	12
10	97	41	92	12	50	96	40	92	13
11	56	36	158	8	51	96	40	92	13
12	97	41	92	12	52	96	40	91	14
13	56	36	158	8	53	97	41	91	13
14	96	40	92	13	54	98	42	91	12
15	95	39	92	14	55	97	41	91	13

16	37	30	240	5	56	96	40	92	13
17	97	41	92	12	57	96	40	92	13
18	96	40	92	13	58	95	39	92	14
19	41	32	220	5	59	96	40	91	14
20	100	50	91	10	60	96	40	92	13
21	97	41	92	12	61	96	40	92	13
22	41	32	220	5	62	97	41	91	13
23	96	40	92	13	63	97	41	91	13
24	96	40	92	13	64	97	41	91	13
25	47	33	192	6	65	99	46	91	11
26	37	30	241	5	66	96	40	92	13
27	95	39	92	14	67	96	40	91	14
28	96	40	92	13	68	97	41	91	13
29	56	36	158	8	69	97	41	92	12
30	97	41	92	12	70	97	41	91	13
31	96	40	92	13	71	97	41	91	13
32	96	40	92	13	72	95	39	92	14
33	47	33	192	6	73	97	41	91	13
34	96	40	92	13	74	97	41	92	12
35	95	39	92	14	75	97	41	91	13
36	95	39	92	14	76	95	39	92	14
37	97	41	92	12	77	47	33	192	6
38	97	41	92	12	78	99	46	91	11
39	96	40	92	13	79	98	42	91	12
40	97	41	91	13	80	97	41	91	13

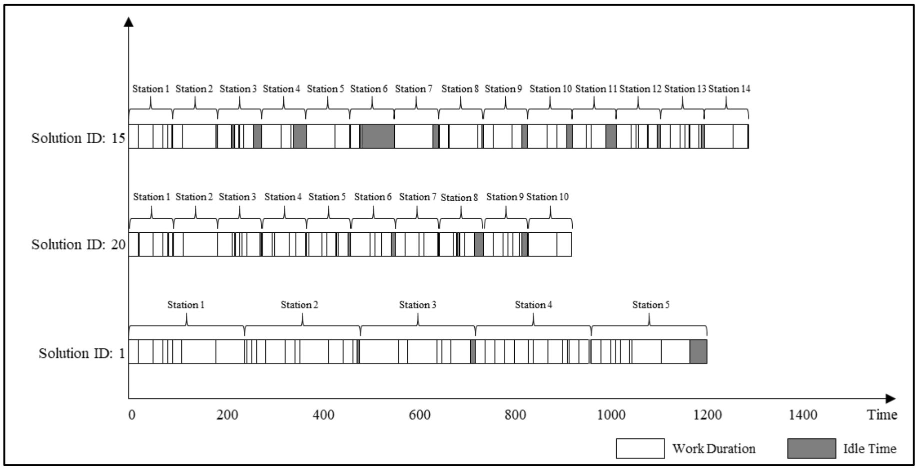


Figure 4-8. Example of optimized production line.

To validate MOMUPL, its results are compared with those of single objective optimization experiments. The objective of first single objective optimization is to minimize the total number of workers, and the objective of second one is to maximize the number of produced units. These are both the objectives of MOMUPL. Figure 4-8 shows the comparison results. In the experiment of labor minimization, MOMUPL shows better results, but the difference is not significant. In each GA optimization experiment, the result changes because GA does not generate an exact solution but rather an optimal solution. Therefore, the difference can be justified. However, in the other single objective optimization experiment for maximization of produced units, the results show significant difference between MOMUPL. The results of MOMUPL cannot be directly compared to the result of single objective optimization because the result is far from the Pareto front area of MOMUPL. However, in terms of productivity, the results can be compared indirectly. In the single objective optimization, to make one unit, 0.67 workers are required. The nearest result of MOMUPL required 0.5 workers. In other words, in terms of labor productivity, MOMUPL generates better results than single objective optimization. However, in terms of multi-objective optimization performance, these results show the limitations of MOMUPL. The goals of multi-objective optimization are to 1) improve result fitness and 2) extend the variation of optimal solutions in the Pareto fronts. In terms of variation, MOMUPL cannot find the result of single objective optimization to maximize produced units. Therefore, a method to extend the variation of solutions is required.

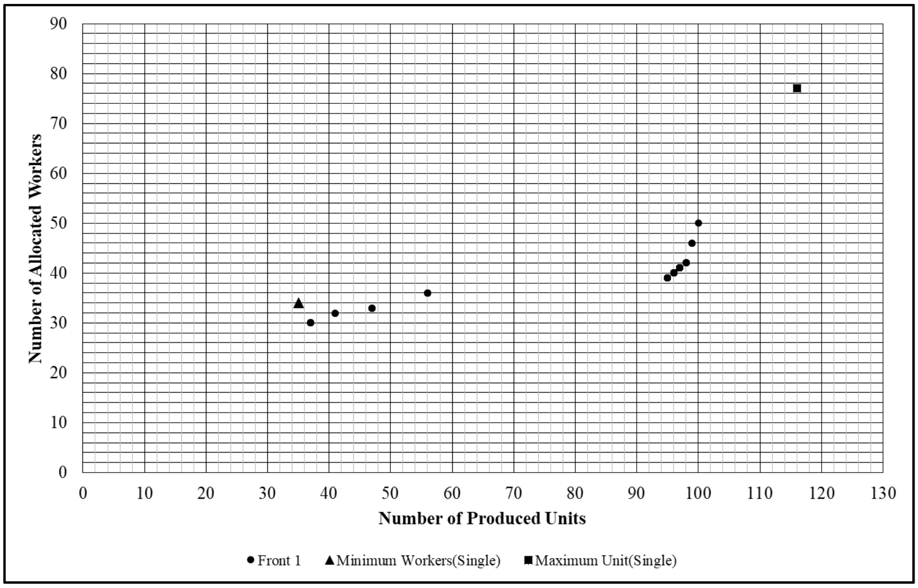


Figure 4-9. Comparison of results for multi and single objective optimization.

4.5 Initialization of MOMUPL

The results of the case study show the limitations of MOMUPL. These limitations mean that in terms of diversity, MOMUPL cannot suggest better results than single objective optimization. In other words, in terms of optimization performance, MOMUPL must be supplemented because diversity of the optimal solution is a major criterion in multi-objective optimization. In the optimization methodologies, such as GA, initialization is used to improve the fitness of each chromosome, and through this improvement, optimization performance is improved. Therefore, the initialization procedure has been designed for each optimization goal. Therefore, to supplement MOMUPL, the goals of the initialization procedure for unit production line design are 1) decrease in computational demand and duration and 2) extension of result diversity to overcome the limitation of MOMUPL. To achieve these goals, an initialization procedure for unit production line is established.

MOMUPL is based on GA, and evolutionary algorithms such as GA have been used to solve nonlinear complex optimization problems, but long computation time is a common drawback for all population-based schemes, especially when the solution space is difficult to explore (Rahnamayan et al., 2007). Theoretically, the population of size can be infinite, but the size of population affects the performance of the optimization process, such as its computation time (Chen et al., 2018; El-Mihoub et al., 2006). Like other population-based meta-heuristic algorithms, NSGA-II begins by randomly generating chromosomes to form a population (Asefi et al., 2014). However, the starting values of chromosomes may be ineffective (Rahnamayan et al., 2007; Todorovski and Rajicic, 2006). Modular production line design has a great number of combinatorial solutions because the design changes according to a number of variables. Therefore, randomly generated chromosomes may generate an inefficient solution, which also increases the duration for finding optimal solutions. Therefore, the first goal of initialization for MOMUPL in determined to be reduction of the computational demand. To improve the computational efficiency in the combinatorial optimization problem, an initialization procedure for modular unit assembly lines is proposed as follows.

In the initialization procedure, the idle time of randomly generated production line solutions and idle time of workers are reduced by modifying the number of allocated workers. By reducing the idle time, the performance of randomly generated solutions can be improved, and the fitness of the initialized solution can be close to the objective function of MOMUPL. Therefore, this initialization procedure can eliminate the solutions with lower performances than the initialized one, and through this elimination, the optimization searching space can be reduced.

The other goal of this initialization procedure is to extend the diversity of the optimal solution, which is major requirement to supplement MOMUPL. In the production line, work duration restricts cycle time because the cycle time cannot be shorter than the longest work duration on the assembly line. The cycle time affects the number of produced units because one unit is produced after one cycle time elapses. Therefore, the range of cycle time variation affects the diversity of the optimization results. Hence, in this initialization procedure, to extend the range of cycle time variation, the work with longer duration than the cycle time is separated to be conducted on multiple stations. Through this iterative initialization procedure, as shown in Figure 4-10, the chromosomes for the initial population are generated and initialized to improve the performance of each chromosome. Diagrams of the decision making in this procedure are shown in Figures 4-11 and 4-12. Each step in the initialization procedure is as follows.

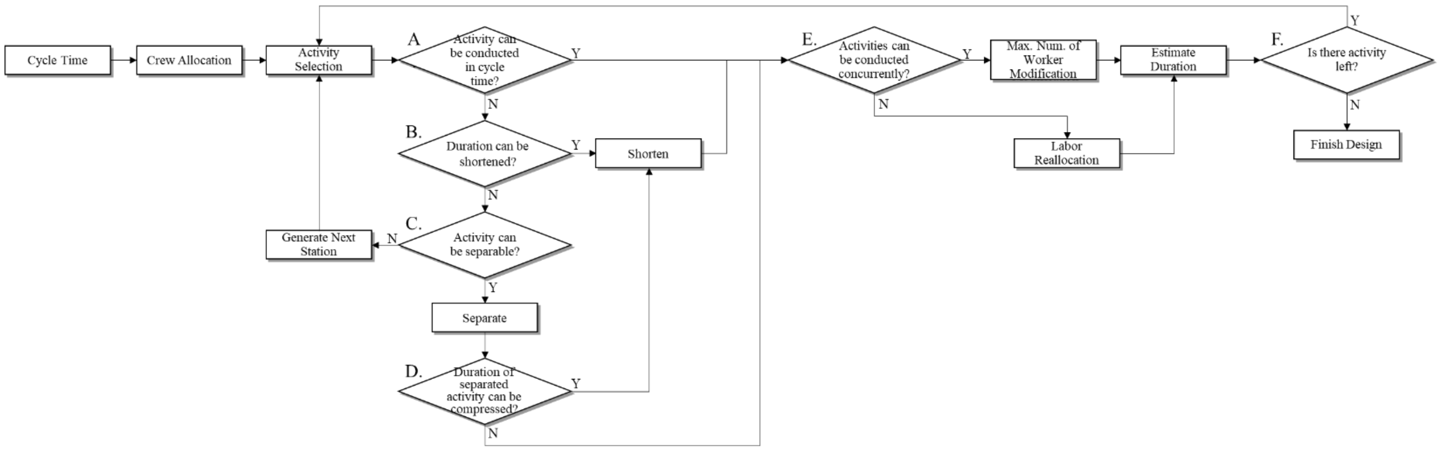


Figure 4-10 Initialization procedure for MOMUPL.

As the first step in the initialization procedure, a certain cycle time of the production line is randomly selected, and the number of workers is also randomly allocated for each activity. The range of random numbers for each gene in a chromosome is determined according to the activity information, such as $MinW_i$ and $MaxW_i$. Then, based on the randomly allocated numbers of workers, the duration of each work (at_i) is estimated. To allocate activity i to station k, the idle cycle time of the station (LCT_k) must be estimated. If LCT_k is longer than at_i, work i is allocated to station k. If not, decision making is conducted to examine whether the duration can be shortened by allocating more workers to work i, as shown by decision B in Figures 4-10 and 4-11. If the duration of work i can be shortened by allocating more workers, more workers are allocated, and the work is included in station k. However, if not, it is examined whether the activity can be separated and conducted on two stations. If the activity cannot be conducted on two stations, the following station is established to allocate the activity. If the activity can be separated, the activity is conducted on two stations as works C1 and C2, as shown in Figure 4-11. If the separated activity duration can be shorter than 5 minutes, the activity is not separated because it would decrease the productivity of workers. Through this separation, the longer activity duration than cycle time can be divided and can be conducted at multiple stations. Therefore, it is possible to modify the work duration and extend the range of cycle time variation. Then, the separated activity C1 is examined as to whether the duration can be further shortened by allocating more workers. If the duration can be further shortened, this is done. Then, the next decision making F is conducted, as shown in Figures 4-10 and 4-11. If it cannot be further shortened, the decision making F is conducted directly. In the decision F in Figure 4-10, it is examined whether the work on the station can be conducted concurrently like activities D and C2 shown in F in Figure 4-11. On the assembly line, there are activities conducted on the insides and outsides of units. When conducting inside work, the activity for exterior work can be conducted concurrently. Therefore, if concurrent work is considered in the production line design, its efficiency can be improved. Hence, in the decision F, the allocated work on the station is examined to identify inside or outside activity. When activities can be conducted concurrently, the maximum number of workers is modified, as shown in Figure 4-12. In the work information, the maximum number of workers is presented to prevent workspace interference caused by allocating more workers than space is allowed for. However, conducting works concurrently does not cause workspace interference, so the maximum number of workers is modified. The modified maximum number is determined as the sum of the maximum number of each activity. If there are no activities that can be conducted concurrently, labor reallocation is conducted to prevent unnecessary crew allocation, as shown in Figure 4-12. If there are works that require the same type of worker on the same station, the workers allocated to work that requires more workers conduct activities according to activity sequence, and workers for the other activity are not allocated. Through labor reallocation, idle time of workers, number of workers, and activity duration can be reduced. After modification or labor reallocation, the idle time in station and duration for conducting the allocated works at a station are estimated to include the following activities, and the abovementioned initialization procedure is conducted iteratively. If there is no activity to be included on the production line, the initialization for a single chromosome is finished. After N iterations of the initialization procedure, an initial population of size N is generated and the newly generated chromosomes by the genetic operator are also initialized.

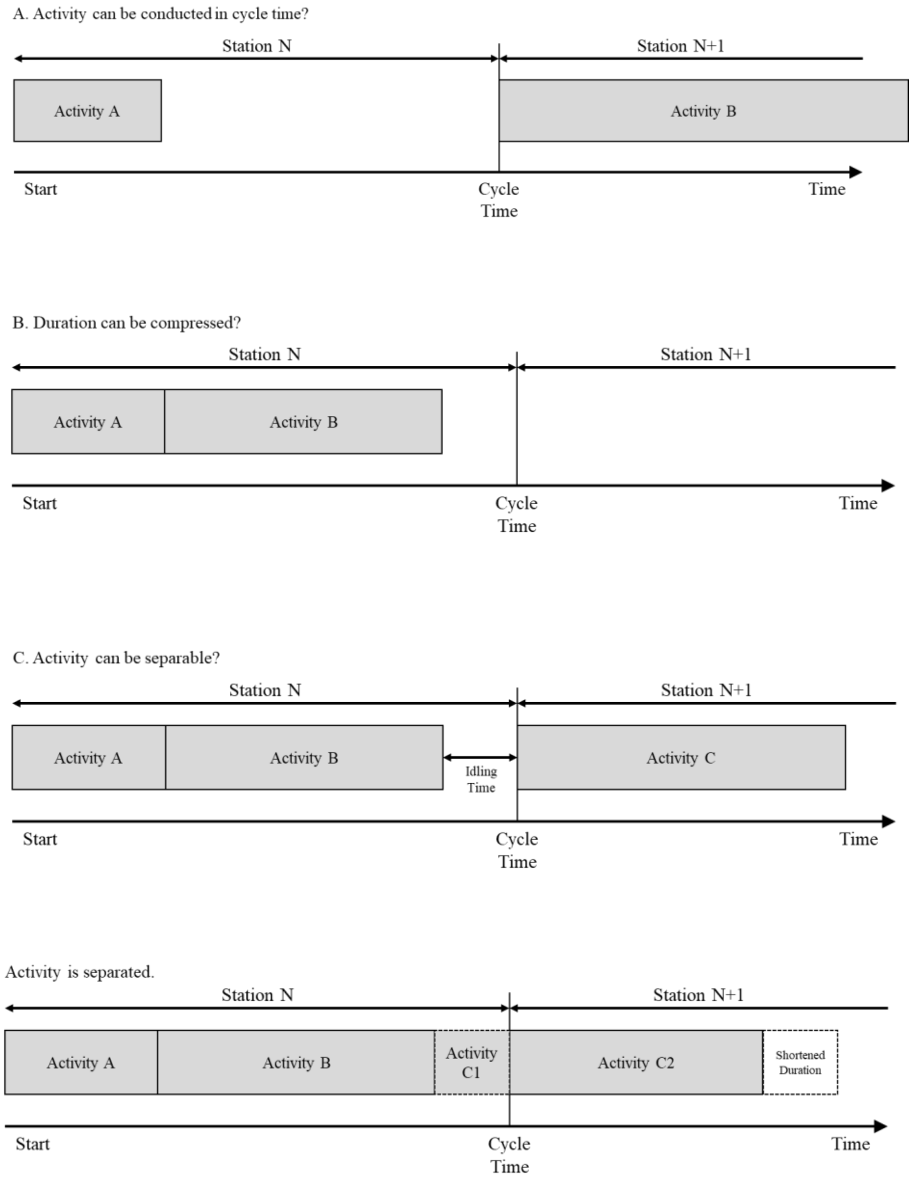


Figure 4-11. Diagram of decision making in initialization procedure.

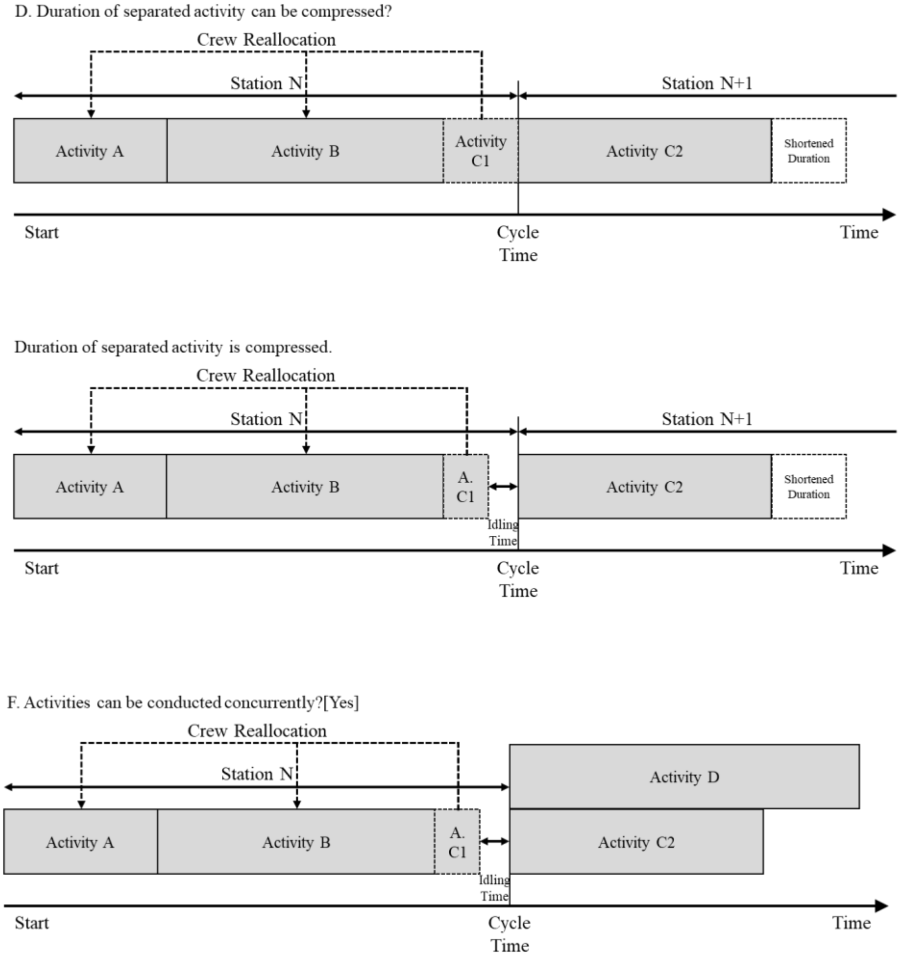


Figure 4-11. Diagram of decision making in initialization procedure.

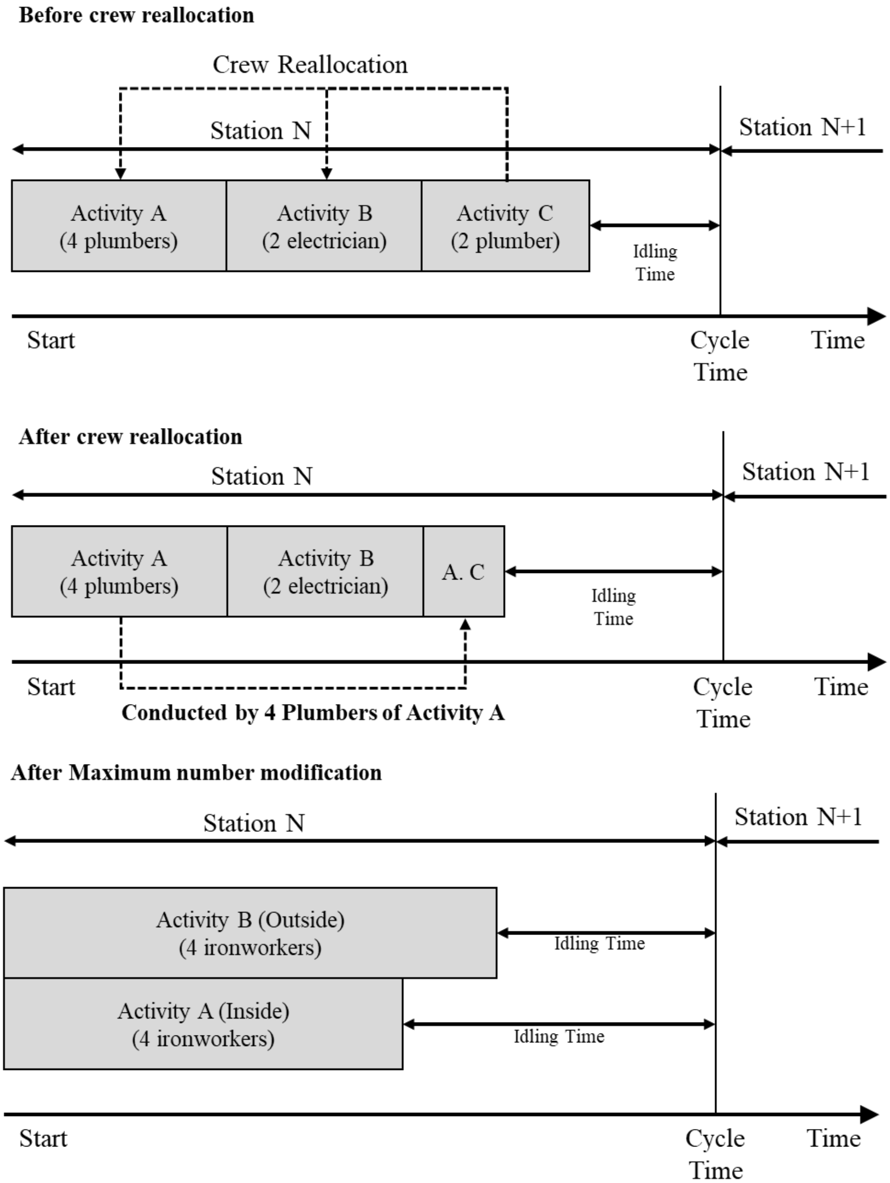


Figure 4-12. Examples of crew reallocation and modification of maximum number of workers.

4.5.1 Initialization Procedure Experiment

To test the effectiveness of the suggested initialization procedure in terms of optimization performance, the results from case studies are compared. The optimization parameter is equal to that of case studies. Figure 4-13 shows the comparison results. The 54 solutions are suggested as optimization results of MOMUPL with the proposed initialization procedure, and Table 4-5 provides information on these results. The results show that the total number of allocated workers ranges from 33 to 84, and the total produced units ranges from 39 to 198. The results also show overlaps, as in the results of case studies. In terms of the number of allocated workers and produced units, the results show differences. Some points of initialized solution sets show lower performance than in the case studies. The reason for the lower performance of initialized results is that when separating the activity in the initialization procedure, the same number of workers are allocated to the divided activity. Hence, the number of workers is doubled. Therefore, if there is a separated activity, the increased number of workers needed causes a decrease in productivity. Moreover, although the solutions of the case studies are randomly generated, the labor reallocation in Figure 4-12 was applied as an assumption. In summary, the activity separation in the initialization procedure can affect the number of allocated workers. However, the other results of initialized solution sets show that the performance results are better. Hence, the distribution of results is generally located below the results without conducting initialization and the results of single objective optimization. In other words, the results with initialization show the highest productivity. In terms of diversity of optimal results, the results of conducting initialization show the best performance. The reason for this is that by separating the activity, the cycle time constraint is alleviated, and the range of cycle time is extended. Therefore, the searching space of optimization is extended, and the bounds of the optimal set are extended. The aim of MOO is to suggest an optimal set to a decision maker. Therefore, the broad variation in the optimal set means that the decision maker can choose the assembly line design according to the demand of the project. Therefore, it can be considered as the contribution of this initialized procedure that the result of this research can embrace the more modular project case than without the initialization procedure. In other words, by using this initialized procedure, some limitations of MOMUPL are overcome, and by using its results, the project manager can cope with flexibility in the modular construction schedule in the planning phase.

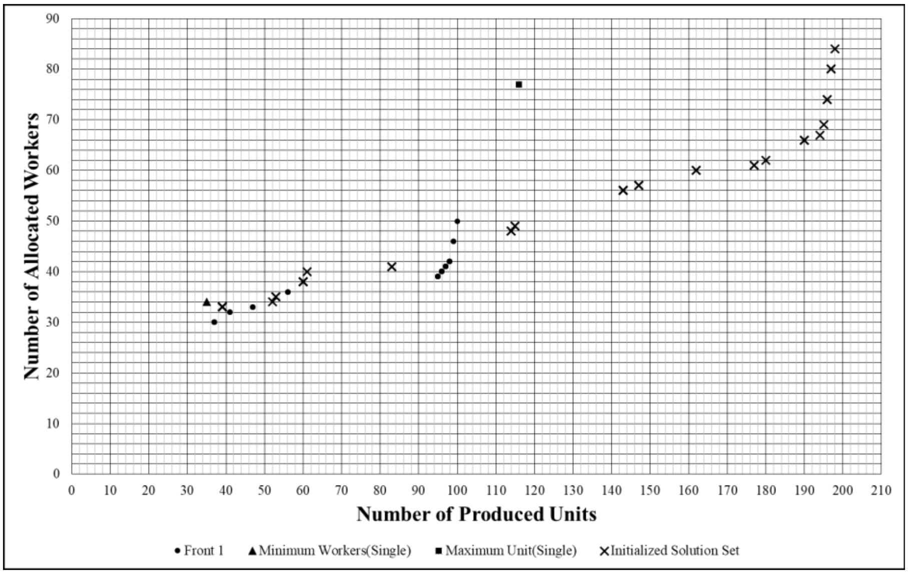


Figure 4-13. Optimization results for MOMUPL with initialization procedure.

Table 4-5. Optimization results for unit production line.

Solution ID	Number of Produced Units	Number of Workers	Cycle Time	Average Idle Time of Workers	Number of Work Stations
1	143	56	63	82.6	16
2	39	33	238	350.9	4
3	162	60	56	73.9	17
4	115	49	79	109.3	12
5	147	57	62	84.0	15
6	147	57	62	84.0	15
7	60	38	153	201.8	6
8	143	56	63	80.8	16
9	143	56	63	82.6	16
10	114	48	79	101.4	13
11	190	66	48	59.3	19
12	39	33	238	357.0	4
13	52	34	176	243.1	5
14	147	57	62	82.2	15
15	39	33	238	354.6	4
16	162	60	56	73.9	17
17	39	33	238	352.3	4
18	114	48	79	100.8	13
19	39	33	238	357.0	4
20	190	66	48	59.3	19
21	60	38	153	201.2	6
22	143	56	63	83.3	16
23	39	33	238	350.9	4
24	143	56	63	80.8	16
25	53	35	175	237.6	5
26	194	67	47	60.4	19
27	143	56	63	83.3	16

Solution ID	Number of Produced Units	Number of Workers	Cycle Time	Average Idle Time of Workers	Number of Work Stations
28	180	62	51	69.7	17
29	61	40	153	209.4	5
30	39	33	238	350.9	4
31	83	41	110	148.3	8
32	53	35	175	235.9	5
33	60	38	153	202.2	6
34	177	61	51	64.1	20
35	196	74	47	63.0	17
36	177	61	51	64.1	20
37	198	84	47	64.2	15
38	39	33	238	352.9	4
39	60	38	153	200.7	6
40	39	33	238	349.1	4
41	39	33	238	347.8	4
42	197	80	47	63.5	16
43	83	41	110	148.3	8
44	115	49	79	108.7	12
45	39	33	238	352.3	4
46	60	38	153	200.5	6
47	195	69	47	60.9	18
48	196	74	47	63.0	17
49	39	33	238	343.5	4
50	39	33	238	343.5	4
51	190	66	48	59.7	19
52	39	33	238	350.5	4
53	197	80	47	63.5	16
54	39	33	238	324.9	4

4.6 Discussions

The solutions in the Pareto front in Figure 4-13 are not superior to any other solution in the same front in terms of multi-objective optimization. However, in terms of productivity, such as the allocated workers per unit, the solution can be ranked, and the range of productivity is significant. Although the decision maker can choose the solution with the highest productivity from the Pareto front, the aim of this research is not to optimize the productivity but to suggest the optimal solution set in the trade-off. The results of this research can be used to find an optimal solution when the resources are a constraint. For example, if the number of workers is limited or if the number of units that should be produced in certain duration is determined, this research can suggest the optimal production line design considering the constraints. Therefore, the project manager can cope with flexibility in the modular construction schedule using the results in the solution set.

In terms of the number of objective functions, the solution considering more objective functions is not necessarily better. MOO is based on a trade-off, which means it aims to mitigate the loss of all criteria. Therefore, it can be said that the project manager must choose the optimization method according to the objective of the modular project and must determine the optimization objective depending on the project's goal.

4.7 Summary

Modular construction consists of unit manufacturing and on-site work processes. A significant proportion of work is conducted in the unit manufacturing process. Therefore, the efficiency of the unit manufacturing assembly line affects the project performance. When designing a modular unit production line, the project manager faces problems in increasing production amount without decreasing labor productivity. Moreover, to embrace flexibility in modular project schedule, it is necessary to suggest various production line solutions. These problems are related to the MOO problem. To identify the characteristics of the modular production line, the scheduling methods of JSS and FSS are compared to the unit production line. The modular production line design, JSS, and FSS are similar in that the optimization problem for them is a complex combinatorial problem. However, the difference is that the modular production line optimization is a problem that considers the allocation of activities and workers to each station.

In this research, to design and suggest various modular production line designs, MOMUPL is developed to suggest an optimal design solution set. In the cost and time trade-off, minimization of the total number of allocated workers and maximization of the number of total produced units are considered as objectives because they are major drivers of modular projects.

To overcome the limitations of MOMUPL, an initialization procedure is suggested and applied to MOMUPL. Through this procedure, the diversity of the results of MOMUPL is extended. 54 optimal solutions are suggested, and each solution has unique design properties. Because the solution sets consist of non-dominated solutions, the project manager can choose any solution according to the objective of their modular project. Based on the production line design, the manufacturing schedule can be determined. Using the various solution sets, the whole modular project schedule can be determined, embracing the flexibility of modular projects.

From the perspective of optimization performance, by the initialization procedure in this research, the optimization performance can be improved in terms of result diversity compared to randomly generated initial solutions and a single optimization solution, which can reduce the duration of the production line design. The limitations of MOMUPL are that 1) it must be validated by applying it to a real modular project or by comparing data generated from a real project, 2) resources other than labor must be considered, and 3) when designing a production line, the other assembly line types, such as the static type, should be considered, but in this research, only the continuous assembly type is considered.

Chapter 5. On-site Work Scheduling Method Using Parallel Station Method

5.1 Modular Construction On-site Work

In modular construction, repetitiveness is considered to be important, as in other construction projects (e.g., highways, high-rise buildings, and rail road constructions) because of its high productivity. To apply repetitiveness to construction projects, repetitive scheduling methods have been used (El-Rayes and Moselhi, 1998; Ioannou and Yang, 2016). In the proposed repetitive scheduling methods, activity duration is set by adjusting production rate a, which optimizes the work schedule. Moreover, to deal with the flexibility of modular construction schedules in the planning phase, the on-site work schedule must cope with various on-site work durations. Therefore, the scheduling method must cover various production rates.

However, when applying repetitive scheduling methods to modular on-site work, there are constraints on production rate adjustment. These constraints cause idle time in schedule. The constraints are caused by the difference in work amount between each activity and workspace limitations for units. For example, when interference between activities is predicted in a repetitive schedule, to prevent interference, the production rate of the preceding activity is accelerated. However, in on-site work, the work space for modular units is limited, and the more workers cannot be inputted to the unit than is approved. Moreover, the workers cannot be allocated to other units to increase production rate because when conducting on-site work, units are being assembled simultaneously. Therefore, the workspace limits the range of production rates, which decreases the optimization efficiency of the repetitive schedule.

In the manufacturing industry, to make production rate flexible, the parallel station method (PSM) has been used (Askin and Zhou, 1997; Becker and Scholl, 2006; PINTO et al., 1981). By applying PSM to modular on-site work, the limited range of production rates can be adjustable. Thus, the on-site work schedule can embrace flexibility of duration. Therefore, the research objective for this chapter is to develop the repetitive scheduling method for modular construction on-site work by applying PSM. To achieve the research objective, the constraints on production rate are analyzed. Repetitive scheduling methods are also analyzed via a literature review to apply the PSM. Then, to validate the PSM, a simulation model is developed using discrete event simulation (DES), and the simulation results are analyzed. Finally, to improve the efficiency of the schedule, repetitive schedules applying the PSM are modified according to project characteristics. The scope of this research is 1) a focus on on-site work related to modular units, excluding transportation, site work, and foundation work, and 2) the resources considered in this research are limited to labor, and other resources are not considered. To apply PSM to the scheduling method, it is assumed that a certain number of units are assembled as a scheduling buffer before on-site work.

5.2 Repetitive Scheduling Method for Modular Construction On-site Work

5.2.1 Constraints of On-site Work Schedule

Most work in modular construction is conducted in a factory, which means construction processes on-site are replaced with faster and more efficient manufacturing processes (Lawson et al., 2011). After the manufacturing process, units are transported to the construction site, and on-site works are conducted. Although most works are conducted in a factory, a certain proportion of the work is conducted on-site, and this proportion is estimated to be from 30 % in fully modular building to more than 50 % (Lawson et al., 2011). In the planning phase, the on-site work is tightly scheduled to be conducted over a short duration. Moreover, through flexibility, various schedule alternatives can be generated. In the alternatives, on-site work and unit production must be balanced to prevent schedule and cost overrun. In this situation, production rate of on-site work activities must be adjusted to cope with the alternatives.

In the on-site work, units are assembled, and to complete construction, on-site work such as finishing work, is conducted in each unit. Therefore, modular construction on-site work can be defined as a process of repetitive activities. To employ the high productivity of repetitive work, scheduling methods for repetitive work have been proposed. In the repetitive scheduling methods, the project schedule is optimized by adjusting production rate of activities. However, the constraints of on-site work limit the range of production rates. One constraint on regulating the upper production rate limit is workspace limitation in modular units. For example, when conducting on-site work, to increase production rate, more workers can be allocated to relevant activities. However, there may be a situation where more workers cannot be inputted to one unit for inside finishing work due to workspace interference. Workers also cannot be inputted to several units because units are being assembled simultaneously, which regulates the increase in production rate. The other constraint contributing to the lower production rate limit is the difference of work amount between activities. In on-site work, there are activities that require little on-site work, and there are activities that are almost entirely conducted on-site. When adjusting the production rates of activities where one or few workers are allocated to slow the working speed, the number of workers cannot be reduced from the minimum, which leads to idling time and loss of productivity. To improve schedule efficiency and to deal with flexibility in the schedule, the constraints, such as workspace limitation and work amount difference, must be overcome.

In stick-built construction, repetitive works are conducted after a certain time for concrete curing. The curing time cuts off the work flow (Reda, 1990). However, modular construction usually does not require curing time on-site.

Therefore, on-site work can be conducted with unit production simultaneously, and each unit can be a work zone for repetitive works, as shown in Figure 5-1.

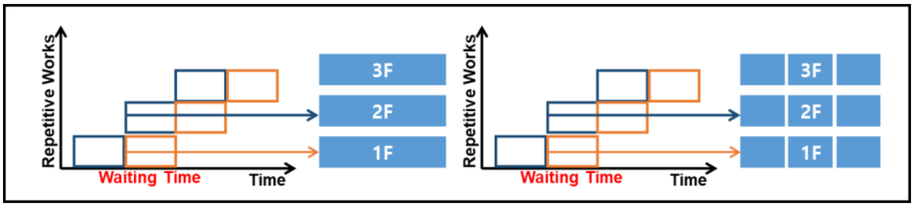


Figure 5-1. Repetitive work in stick-built and modular construction.

In the repetitive schedule, when the divided work area is smaller, the idle time between activities can be reduced, which is related to reduced project duration, as shown in Figure 5-2. This is because the following work can start after the previous work activity is finished. In modular construction, the minimum work load can be determined as each unit. Therefore, the production rate should be determined considering the work amount of each unit.

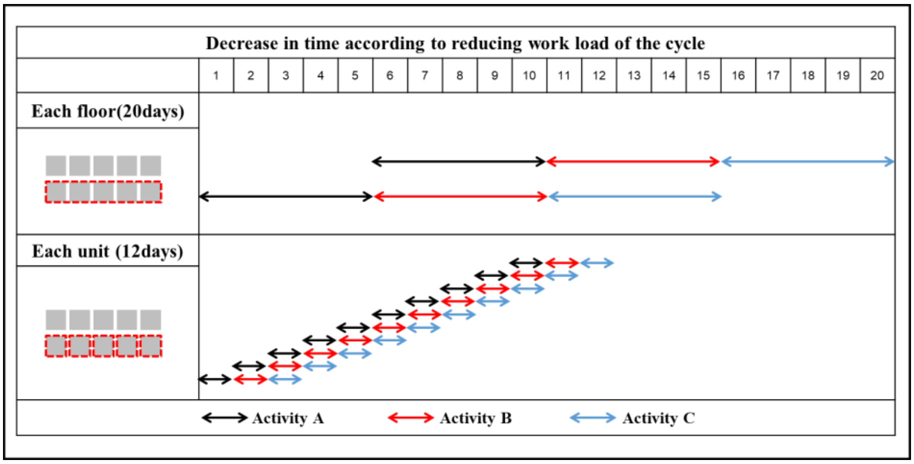


Figure 5-2. Idle time in repetitive schedule according to work load.

5.2.2 Construction Scheduling Methods for Repetitive Projects

In on-site work, the same work activities are conducted in each unit, which increases the labor productivity by repetitive work (Mullens, 2011; Shaked and Warszawski, 1992). In a repetitive project, crew allocation is considered as an important factor because a constant production rate and work continuity are affected by crew allocation (Carr and Meyer; Cho et al.; El-Rayes and Moselhi; El-Rayes and Moselhi; Ioannou and Yang; Ipsilandis; Reda). A constant production rate means conducting all works equally. In this situation, the works are conducted by a specific number of workers according to the kind of works to comply with the production rate (Reda, 1990). If the production rate is not maintained constant, the number of workers fluctuates, which reduces the high labor productivity of repetitive works. Moreover, if the production rate is not maintained constant, it is difficult to predict interference occurrences between activities, which increases project duration. Work continuity means that the activity continues without idle time. To improve work continuity, the idle time caused by waiting time until the preceding workers finish their works should be minimized (Reda, 1990). To schedule repetitive work with a constant production rate and work continuity, several approaches have been applied to the project.

The critical path method (CPM) is duration-oriented and clearly represents a precedence relationship. The project period is adjusted by modifying the activity duration on the critical path (Yamin and Harmelink, 2001). However, when representing a repetitive project, CPM presents a large number of activities, which makes visualization difficult (Reda, 1990). Further, CPM does not necessarily ensure maintained work continuity because the idling time caused by the preceding work with slow production rates is not considered (Reda, 1990). As shown in Figure 5-3, activity B cannot be finished until activity A is finished because the activities are related. Hence, if activity B has a faster production rate than activity A, idling time will occur. In addition, when it is necessary to reduce the project duration in the CPM, the durations of critical activities are shortened by allocating more resources to those activities, which may result in modification of the production rates of other activities, which may be detrimental (Reda, 1990).

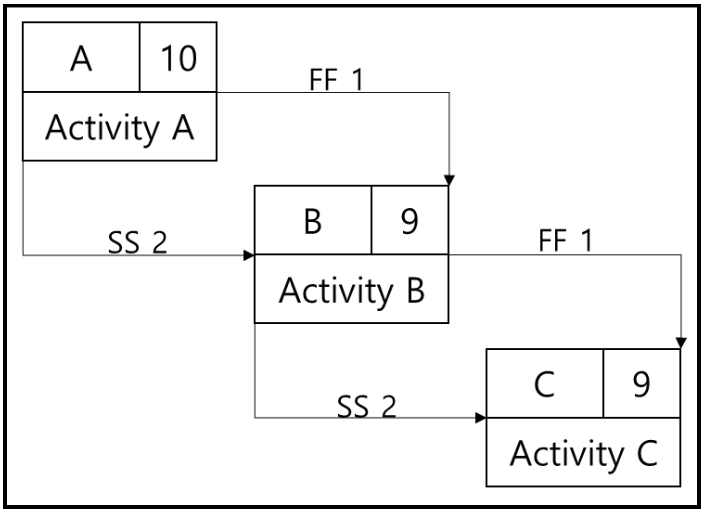


Figure 5-3. Activity relationship in CPM.

To overcome the disadvantages of CPM, line-based scheduling methods and the TACT method have been used (Arditi and Albulak, 1986; Carr and Meyer, 1974; Chrzanowski Jr and Johnston, 1986; Ipsilandis, 2006; Johnston, 1981; Lee et al., 2015; O'Brien, 1975; Reda, 1990). In line-based scheduling methods, such as line of balance (LOB), repetitive activities are represented as lines with constant or varying slope, where the slope indicates the production rate of activities (Reda, 1990). The advantages of line-based approaches are their simplicity, continuity of work, and constant production rate. The work continuity of each activity can be maintained because the collapse between preceding work and following work can be predicted easily. Based on this prediction, a constant production rate can be scheduled in the planning stage by allocating idle time and by modifying the production rates of activities (Reda, 1990). However, when a line-based scheduling method does not synchronize the production rate of each activity uniformly, idling time between activities will occur, as shown in Figure 5-4 (Lee et al., 2015). For example, if certain activities have higher production rates than their preceding activities, interference will occur. This interference creates idle time because the following activity should wait until the interference disappears, and this interference could affect other activities. This means that the line-based method maintains work continuity of each activity, but when the production rate of the preceding activity is different to that of the following activity, idling time between activities occurs.

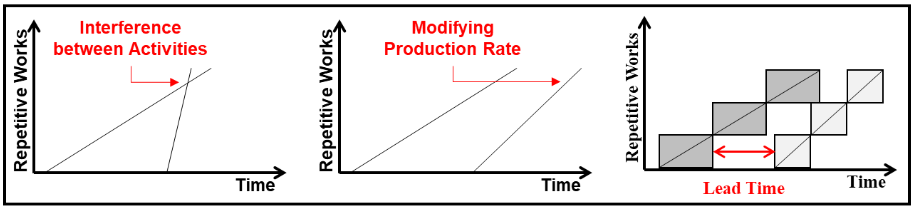


Figure 5-4. LOB scheduling method and idle time between activities.

To reduce the idling time in LOB, the TACT scheduling method is used to schedule repetitive works. The TACT method synchronizes the production rates of activities and allocates the cycle time of repetitive works by zoning work places and maintaining work continuity with a proper number of workers (Lee et al., 2015). In the TACT method, the work activities are grouped for conducting the divided work amount, and the work durations for each activity are equally assigned, which reduces the idling time by synchronizing activity durations, as shown in Figure 5-5. However, each activity requires a different number of workers and has different work characteristics. Therefore, when modifying the activity production rate for meeting the cycling time, idle time of activities will occur because it is difficult to adjust the activity production rate to fit the cycling time accurately, as shown in Figure 5-6. In short, although scheduling methods such as LOB and TACT are used for repetitive works, idle time occurs due to the methods' characteristics. In the LOB method, productivity of workers is increased by maintaining constant production rates and work continuity, but the total project period increases due to idling time between activities. In the TACT method, the total project period is reduced by decreased the idling time between activities, but the idling time in Figure 5-6 reduces the productivity of workers. In the TACT method, by modifying the cycling time in consideration of the idling time, constant production rates and work continuity can be maintained with a short project period. Ideally, when the production rate of each activity in the LOB method can be synchronized, which means the TACT method has no idling time in Figure 5-6, work continuity, constant production rate, and reduced idling time between activities can be achieved. However, in modular construction on-site work, there are constraints on modifying production rate. Hence, when using LOB and TACT, idling time occurs via constraints on modular construction, such as difference in work amount and workspace limitations.

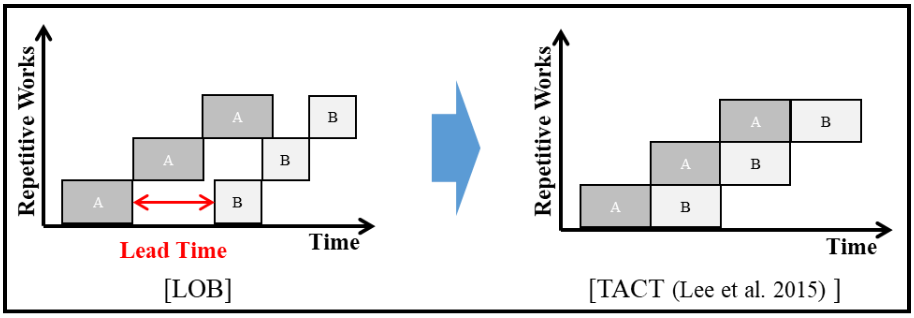


Figure 5-5. Reduced idle time in TACT scheduling method.

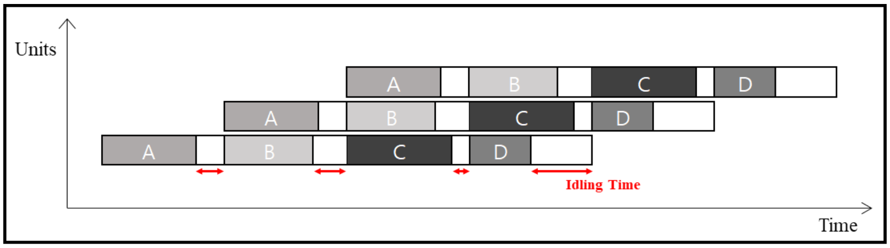


Figure 5-6. Idle time in TACT scheduling method.

5.2.3 Adjustment of Production Rate in Repetitive Schedule

To improve the efficiency of a repetitive work schedule, the idling time must be minimized; idling time can be managed by adjusting the production rates. To optimize the schedule, many studies have been conducted with a focus on adjusting the production rates, as shown in Table 5-1 (Arditi et al., 2002; Ipsilandis, 2007; Nassar, 2011; Zou et al., 2016). However, the results of these studies are based on production rate adjustment without constraints, and the production rates are adjusted to find optimization results. Arditi et al. (2002) suggested basic principles that can be used in planning repetitive scheduling and explained that an optimal repetitive schedule can be achieved by adjusting production rates and crew size. Then, strategies are suggested to accelerate the production rate in the LOB method by adjusting crew size. However, the constraint on adjusting production rate is not described. In other words, the repetitive schedule can be optimized by adjusting the production rate of activities, and the constraints on adjustment of production rate range limit the improvement of the optimization results for a repetitive schedule. For improvement of modular construction on-site work schedules, the constraints on production rate adjustment should be overcome to increase or decrease the production rate in the scheduling method.

Table 5-1. Previous research on repetitive scheduling methods.

Authors	Body of Research	Objective	Production Rate
Nassar (2011)	Schedule optimization	Minimization of project duration and interruption days	Not regulated
Ipsilandis (2007)	Schedule optimization for linear repetitive projects	Optimization of multiple objectives, such as duration, idle time of resources, and delivery time of project's units	Not regulated
Zou et al. (2016)	Schedule optimization using MILP approach.	Minimization of project cost with minimized delay	Not regulated
Arditi and Albulak (1986)	Description of principles for computerized LOB system considering the issues in LOB	Strategies to overcome the issues in LOB method	Not regulated

5.2.4 Parallel Station Method

In the manufacturing industry, to improve flexibility of production rate, the PSM has been used (Askin and Zhou, 1997; Becker and Scholl, 2006; PINTO et al., 1981). The PSM can increase production rates by enabling activities that require longer than the cycle time to complete to be conducted in a two-sided (parallel) line so that workers can conduct activities simultaneously. Thus, the activity can be completed within the allocated cycling time as the activity duration is reduced by a half. The PSM is a solution to making the production rate of on-site work more adjustable and extendable. Thus, the on-site work schedule can cope with flexibility by extending the range of production rates. In particular, if one or more activity times are greater than the desired cycle time in the TACT method, the PSM can resolve this conflict, and the production rate in the LOB method can be adjusted without workspace interference, as shown in Figure 5-7. For example, when the determined activity cycle time is 1 h in the TACT method, the productivity of electronic work can significantly decrease due to workspace interference. To solve the workspace problem without decreasing productivity, the activity cycle time of electronic work can be modified to 2 h while fixing the number of workers. Then, the workers conduct the activity for two modular units, and the following plumbing connecting work for one unit is completed in 1 h, as shown in Figure 5-7. As shown in Figure 5-7, the electrical work amount for two modular units is finished with the same resources, where half of the original number of workers are assigned to each unit so that workspace interference can be reduced. Moreover, the allocated time for plumbing connecting work can be maintained at 1 h, which can reduce idling time. Therefore, the PSM allows the production rate in modular on-site work the be adjusted with the objective of reducing idling time. In other words, repetitive scheduling methods in combination with the PSM can be used for modular on-site work without constraints on production rate adjustment.

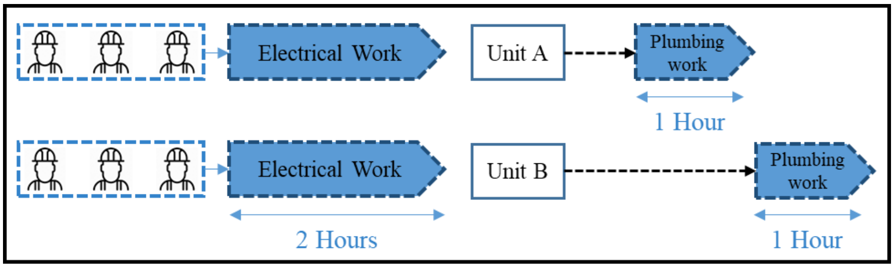


Figure 5-7. Crew allocation in parallel station method.

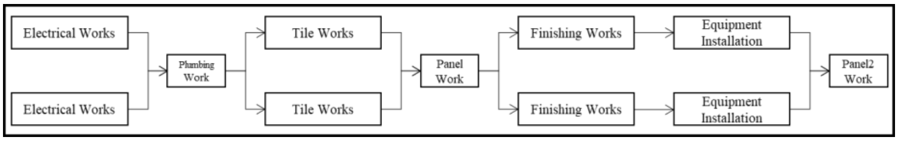


Figure 5-8. Parallel station method for modular construction on-site work.

5.3 On-site Work Scheduling Model Development

5.3.1 Model Development

To validate the scheduling method using the PSM quantitatively and to estimate idling time, on-site work duration, and the number of workers, a simulation model is developed. As a simulation methodology, DES is used. Modular construction on-site work can be represented as a sequence of activities, and DES focuses on the process level based on the queuing theory (AbouRizk et al., 1992; Lee et al., 2007). DES can provide information about the activities and resources required to conduct work activities. Thus, DES can be used to develop a simulation model of modular on-site work for monitoring the results according to changes in the production rate and cycling time; it can also estimate the number of workers to be allocated. As a simulation modeling tool, Anylogic 7.0 PLE is used. For model development, a military facility modular construction project is used as a case project. The project information is presented in Table 5-2. The developed model describes on-site work processes, while excluding transportation and unit assembly, as shown in Figure 5-7. In this model, seven types of activities are conducted, and workers conducting activities are allocated to each activity as resources. A unit is considered as completed when it has been subjected to all the activities in the process. The on-site work in this model starts when the first unit is assembled and finishes when the last activity is completed for the last unit. The activity production rates are adjusted based on the number of workers. Then, the number of units, which represent work amount, is adjusted to apply the PSM. Buffers are placed between activities. The time spent in buffers is considered as idling time. When an activity is completed, the unit is stored in the buffer until the idling time, which is established to prevent interference between activities in LOB or cycle time in the TACT method elapsing.

Table 5-2. Project information for modular construction project.

	Modular Construction Project Information
Location	Jangdan-myeon, Paju-si, Gyeonggi-do, Republic of Korea
Building Type	Military Facility (Barracks)
Height	1 story
Project Duration	05.09.12 - 05.11.01 (51 days) (Off-site: 28 days; On-site: 23 days)
Number of Units	30

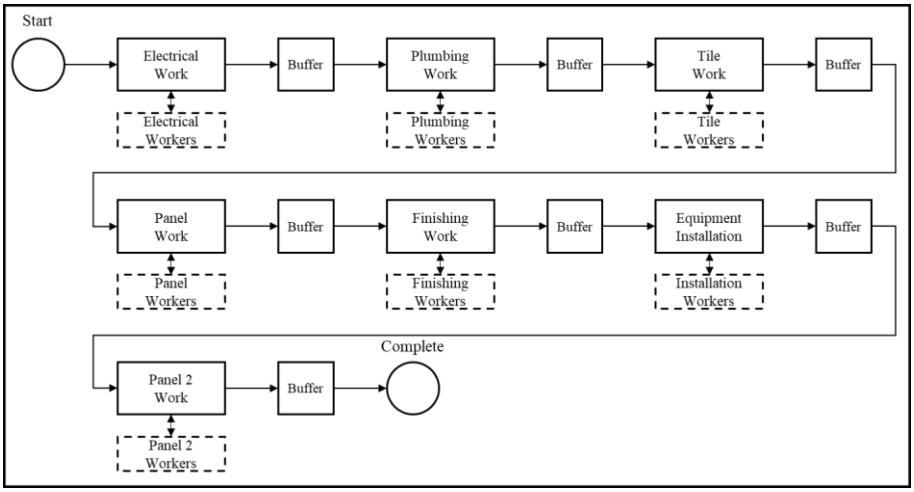


Figure 5-9. Modular construction on-site work process in simulation model.

5.3.2 Model Verification

To confirm the reliability of the developed simulation model, model verification is conducted. If the model verification results, such as the total number of workers, activity duration, and total on-site work duration, agree with the project case data under similar conditions, the model is considered reliable and appropriate for testing other conditions, such as those in repetitive scheduling methods applying the PSM. Accordingly, conditions similar to the project data are applied to the simulation model for verification. The numbers of workers required to conduct activities are listed in Table 5-3 and used as input values; these are rounded up based on the number of workers per day in the project data. The total on-site work amount is set to 30 units. In fact, the activities in the project were conducted at certain time intervals to increase the utilization rate of workers by maintaining work continuity. In the developed model, the intervals between activities are estimated based on the production rates of the previous activities. For example, in the project, plumbing work starts after the fourth day of electrical work. During these four days, electrical work for 13.2 units can be conducted. Thus, the plumbing work starts when electrical work for 14 units has been completed and the idling times between other activities are allocated in the same manner. The project data and verification results are compared in Table

5-4. The verification results show that the on-site duration is 22 days, which is the same as that in the project data. However, there is a difference in the total number of workers. The reason for this is that the allocated number of workers for each activity is rounded up, and the difference between the actual and estimated durations of each activity is represented as a difference in the input number of workers. This difference is attributable to how the total number of workers is estimated by multiplying the activity working days with the input number of workers. Furthermore, in the simulation, some activities started in the afternoon as the work starting time is not regulated, which also constitutes a difference in input workers. By comparing the project data and verification results, it can be regarded as reliable that this model represents on-site modular construction work and can be employed to test other scheduling conditions.

Table 5-3. Number of workers inputted to model.

	On-site Work Activities						
	Electrical Work	Plumbing Work	Tile Work	Panel Work	Finishing Work	Equipment Installation	Panel Joint
Completion time by one worker	5.76	2.12	6.5	2.12	7.47	4.27	1.6
Activity Duration (days)	9	4	5	4	5	5	3
Workers/day	2.4	2	5	2	5.6	3.2	2
Input value	3	2	5	2	6	4	2

Table 5-4. Model verification results.

		On-site Work Activities							
		Electrical Work	Plumbing Work	Tile Work	Panel Work	Finishing Work	Equipment Installation	Panel Joint	Total Workers
Total Number of Workers	Project Data	22	8	25	8	28	16	6	113
	Simulation Result	24	12	30	10	30	20	8	132
On-site Work Duration	Project Data	2005.10.10 ~ 2005.10.31 (22 DAYS)							
	Simulation Result	2017.03.14 ~ 2017.04.04 (22 DAYS)							

5.4 Simulation Experiments

5.4.1 Simulation Information

To estimate and compare the number of inputted workers and on-site work duration of repetitive scheduling methods for stick-build construction and repetitive scheduling applying the PSM, simulation experiments are conducted. The experiments are conducted individually for each scheduling method. In each simulation experiment, the established production rates of each scheduling method are inputted by adjusting the numbers of workers. The idling times, which are estimated considering the production rate of each activity, are allocated to prevent interference between activities. To consider the workspace per unit, the maximum number of workers in a unit is limited to four, and although the work amount is small, which causes idling time, one worker is allocated for conducting each activity. Table 5-5 shows the simulation experiment information and results.

As the first experiment, the LOB method is simulated, and the production rates of activities were set to 2 h/unit to reduce the idling time between activities. The reason for establishing the production rate as 2 h/unit is that finishing work requires the longest duration for one worker, and by inputting four workers, the duration can be reduced by approximately 1.87 h, which is the maximum production rate in LOB. Therefore, to reduce idling time between activities in LOB, the production rate of each activity is set to approximately 2 h/unit. The idling times between activities are allocated to prevent interference. During idling time, the units are stored in the buffer storage in the model, and the following activity starts when the idling time has elapsed.

Then, the TACT method is also simulated, and the notion of cycle time is employed. The activity cycle time in the TACT method is set to 2 h/unit for a fair comparison between the LOB and TACT methods. After 2 h, the units being processed proceed to the next activity, and the number of workers required to finish the activity in 2 h are allocated. Although the activities are completed within 2 h, the units are prevented from proceeding to the next activity, which is signaled as idling time.

Finally, TACT applying the PSM is simulated. In this method, as shown in Figure 5-8, the cycle time is set to 1 h/unit, and when adjusting the cycle time from 2 h to 1 h, the PSM is applied to the activities that require more than 4 workers. To increase the production rates of electrical, tile, finishing, and equipment installation works, the numbers of workers for these activities are doubled, and two units are inputted for the activities. For example, to conduct electrical work for two units, three workers are allocated to each unit and conduct work for 2 h. After 2 h, workers allocated to plumbing work conduct their work for one unit in 1 h. Thus, the production rate can be increased without workspace interference.

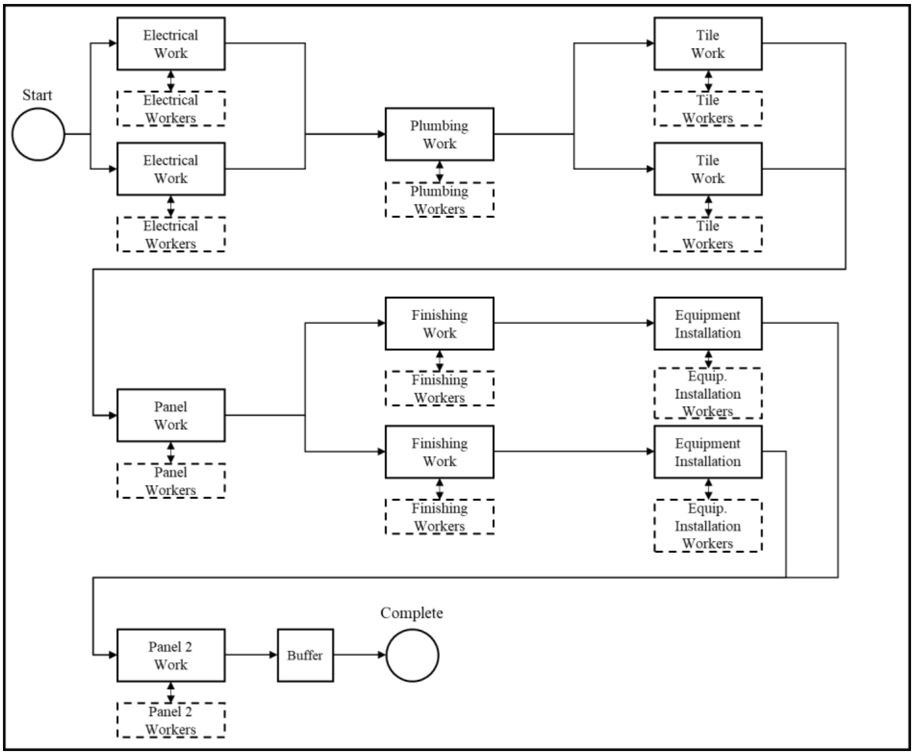


Figure 5-10. On-site work process for TACT applying the PSM.

Table 5-5. Simulation information and results of scheduling methods.

	LOB (2 h/unit)			TACT (2 h/unit)			TACT using PSM (1 h/unit)		
	Allocated Workers	Activity Duration	Input Workers	Allocated Workers	Activity Duration	Input Workers	Allocated Workers	Activity Duration	Input Workers
Electrical Works	3	1.92	24	3	1.92	24	3X2 (6)	1.92	24
Plumbing Works	1	2.12	9	2	1.06	16	3	0.71	15
Tile Works	3	2.17	30	4	1.63	36	4X2 (8)	1.63	40
Panel Works	1	2.12	9	2	1.06	16	3	0.71	12
Finishing Works	4	1.87	36	4	1.87	32	4X2 (8)	1.87	32
Equipment Installation	2	2.14	20	3	1.42	27	3X2 (6)	1.42	30
Panel2 Works	1	1.6	9	1	1.6	9	2	0.8	8
Sum	15	13.94	137	19	10.56	160	36	9.06	161
Total Duration		15 Days			13 Days			9 Days	

5.4.2 Simulation Result Analysis

The simulation results of scheduling methods are obtained using the developed model. The results are compared in Table 5-5. The results show that to complete the modular project, LOB requires 15 days with 137 workers, TACT requires 13 days with 160 workers, and TACT applying the PSM requires 9 days with 161 workers. The results demonstrate an inverse relation between the on-site work duration and total number of workers.

The LOB scheduling method required the longest on-site work duration among the scheduling methods because idling time between activities was allocated to avoid interference between activities. Evidently, such idling time increased the total on-site work duration, but work continuity between activities was maintained, meaning the total number of workers was reduced. The total number of workers and duration of TACT applying the PSM yielded more effective results than the TACT method alone because the PSM managed the production rate to reduce the idling times of activities.

The shorter activity cycle time in repetitive scheduling methods means a shorter on-site work duration and can reduce the idle time caused by different work amounts for each activity, as shown in Table 5-6 (e.g., when cycle time is 1 h, idle time is 1.126, but when cycle time is 3 h, idle time is 4.31 while completing one unit in the project). Therefore, it can be said that application of the PSM can reduce on-site work duration by reducing idling time in the work schedule.

Table 5-6. Idle time in TACT method according to cycle time.

Activity	Time Taken by One Worker	Activity Time in TACT Method		
		1 h	2 h	3 h
		Estimated Time	Estimated Time	Estimated Time
Electronic Works	5.76	0.96 (6)	1.92 (3)	2.88 (2)
Service Works	2.12	0.7 (3)	1.06 (2)	2.12 (1)
Tile Works	6.5	0.93 (7)	1.625 (4)	2.16 (3)
Panel Works	2.12	0.7 (3)	1.06 (2)	2.12 (1)
Finishing Works	7.47	0.93 (8)	1.87 (4)	2.49 (3)
Service2 Works	4.27	0.854 (5)	1.42 (3)	2.32 (2)
Panel Joint Works	1.6	0.8 (2)	1.6 (1)	1.6 (1)
Idling Time		1.126	3.445	4.31

5.5 Modification of Scheduling Methods

To improve the LOB and TACT applying the PSM, the scheduling methods are modified. First, the benefits of the PSM can be applied to the LOB method (LOB+P). For example, when twice as many workers are inputted to conduct activities for two units, the production rate can be doubled. By adjusting the production rate in LOB, the activity rates are set to be relatively uniform, which can reduce the idling times between activities as well as on-site work duration, as shown in Figure 5-9. To apply the benefit of work continuity in the LOB method to TACT applying the PSM, a buffer can be used to reduce the idling time (P+LOB). With a buffer, certain activity on a unit need not be postponed until the cycle time has elapsed when the previous activity is completed; instead, workers can proceed to the next unit. The completed unit goes to the buffer to wait until the workers complete the following activity. When the workers have completed the following activity for a unit, the workers conduct the activity for the unit in the buffer. A diagram illustrating the modified scheduling method is shown in Figure 5-10.

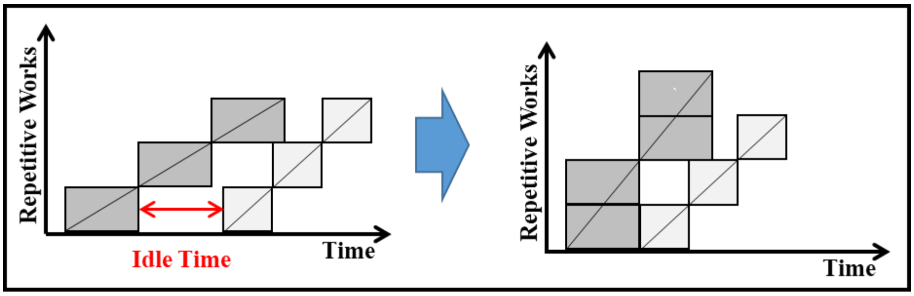


Figure 5-11. Production rate modification in LOB+P.

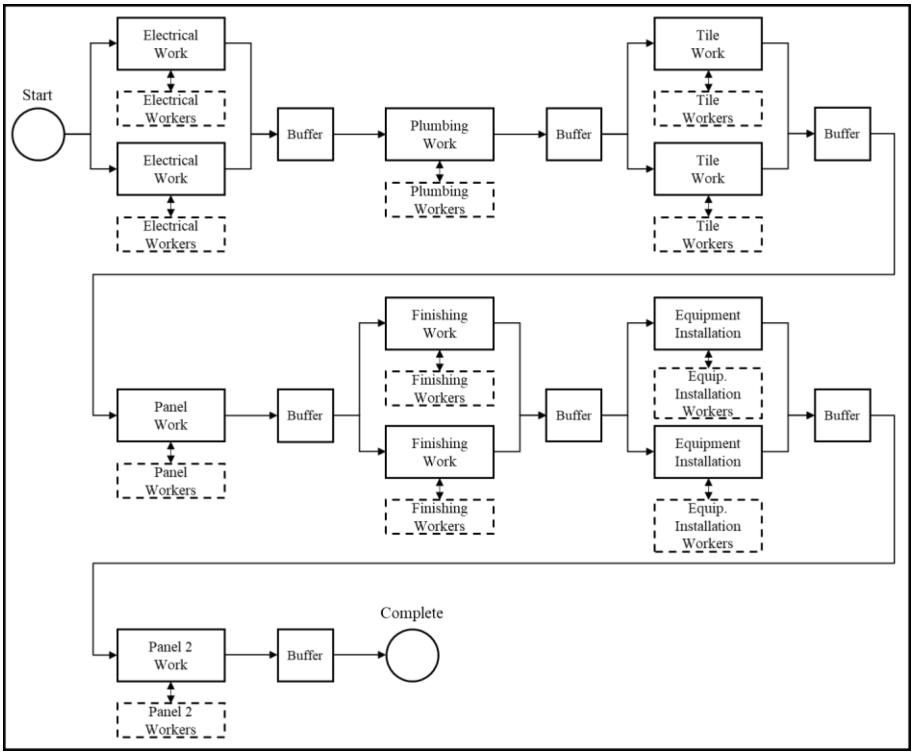


Figure 5-12. Process of modified scheduling method.

To test the effectiveness of the modified scheduling methods of LOB+P and P+LOB, the number of units in the simulation model is increased from 30 to 300, and the results are presented in Table 5-7.

Table 5-7. Simulation results for LOB+P and P+LOB.

	LOB+P (2 h/unit)			P+LOB (1 h/unit)		
	Allocated Workers	Activity Duration	Input Workers	Allocated Workers	Activity Duration	Input Workers
Electrical Works	3X2 (6)	1.92	216	3X2 (6)	1.92	216
Plumbing Works	3	0.71	78	3	0.71	108
Tile Works	4X2 (8)	1.63	240	4X2 (8)	1.63	288
Panel Works	3	0.71	81	3	0.77	108
Finishing Works	4X2 (8)	1.87	280	4X2 (8)	1.87	280
Equipment Installation	3X2 (6)	1.42	162	3X2 (6)	1.42	216
Panel2 Works	2	0.8	60	2	0.8	72
Sum	36	9.06	1117	36	9.12	1288
Total Duration		71 Days			41 Days	

The simulation results demonstrate that the LOB+P method performed better than the LOB method, and the P+LOB method performed better than the TACT method using the PSM. The effectiveness of the modified method can be demonstrated by arithmetic calculation. However, the results also show an inverse relationship between the on-site work duration and total number of workers. Thus, it can be said that the LOB+P method is cost-oriented, while the P+LOB method is time-oriented. Although the PSM can improve the efficiency of the on-site work schedule, the project manager should choose an appropriate on-site scheduling method in accordance with the purpose of their modular construction project to increase its efficiency.

5.6 Discussions

When the duration of activities in P+LOB is set to a fit cycle time, idle time does not exist in the schedule, and P+LOB becomes similar to LOB+P. However, in a practical situation, idle time exists, meaning that the project manager should choose an optimal scheduling method for project efficiency. In that case, the project manager can use the modified scheduling methods to plan, estimate, and predict the on-site work schedule. It is important to consider the on-site work schedule before conducting a modular project because when conducting on-site work, activities are conducted to tight schedules simultaneously. Therefore, the schedule overrun of on-site work is directly related to the project schedule overrun, and this is the reason that this research focuses on on-site work although a relatively smaller proportion of work is conducted than unit manufacturing process. To improve this research and estimate the project duration, the relationships between manufacturing schedule and other on-site work, such as foundation work, are required.

5.7 Summary

Modular construction consists of unit manufacturing processes and on-site work processes. Modular construction on-site work consists of repetitive work activities. To improve the efficiency of repetitive on-site work, repetitive scheduling methods have been used. However, when applying the repetitive scheduling methods intended for stick-built construction to modular on-site work, idle time inevitably occurs because of the limited range of production rates caused by the workspace and difference in work amount of each activity. Moreover, the limited range hinders the embracing of flexibility in the modular construction schedule.

With the intent of overcoming these limitations, the constraints on on-site modular construction work were investigated, and the reasons for the occurrence of idling time were analyzed. Using the PSM, the idling time occurring with the repetitive scheduling method can be reduced. Then, the scheduling methods were modified to improve the efficiencies of LOB and TACT applying the PSM. The suggested scheduling methods, namely LOB+P and P+LOB, yielded better results than the modified LOB and TACT applying the PSM. The results also revealed that the LOB+P method is cost-effective, while the P+LOB method is time-effective, implying that the primary objective of a modular project should be identified when choosing the scheduling method in the planning stage.

By using the results of the developed simulation model, the idle time in repetitive scheduling methods can be reduced. The on-site work duration also can be predicted more accurately than using existing methods, and on-site work can be scheduled tightly. The improved schedule efficiency can alleviate the labor shortage problem in the construction industry. The other value of this research is that by using the developed simulation model, alternative work schedules can be considered in a controlled environment, and the effectiveness of the PSM can be tested without other influences.

However, although the workspace limitations differ depending on the types of activities and project, this research applied workspace limitations uniformly. To apply the proposed method to on-site work, it is necessary to estimate the workspace required for each activity to regulate the number of workers in each unit. To supplement this limitation, the estimated workspace data and other major factors affecting the on-site work duration, such as material and modular unit manufacturing schedule, must be included in the developed model.

Chapter 6. Conclusions

6.1 Summary

The construction industry is labor intensive and is suffering from the labor shortage problem. To alleviate this problem, productivity improvement in the construction industry is required. Modular construction has been recognized internationally as offering numerous benefits to most parties in the construction process, such as improved productivity, short construction period, high quality, lower cost, and safety assurances. Therefore, modular construction has been used as a solution to the labor shortage problem and to improve project performances. The benefits of modular construction are based on a significant proportion of unit manufacturing being conducted in an environmentally controlled factory. Hence, the high productivity of the manufacturing industry can be applied to the construction industry, and the risk of on-site environment conditions can be reduced. Moreover, unit production and on-site work can be conducted simultaneously, and the construction period can be reduced. However, the overlapped duration changes depending on the project's characteristics, and the duration is determined in the planning phase. Therefore, a scheduling method for modular construction is required to ensure flexibility in the planning phase.

This flexibility means that there can be various project schedule alternatives. In other words, it is necessary for various unit production and on-site work schedule alternatives to be generated to cope with project schedule alternatives.

In this dissertation, to deal with flexibility, a modular construction scheduling method was proposed based on crew allocation. First, to determine the work proportions of unit production and on-site work and to establish work planning, an integrated modular construction planning process was proposed, with a focus on reducing rework in modular projects. When conducting modular project, rework occurs. This rework means changes to the established project schedule, which causes cost and schedule overruns. A significant proportion of reworks are caused by design errors. To reduce design errors, the project participants should be incorporated into the early design and planning phase. However, because of the complex information flow and lack of expertise and management knowledge of modular construction, a comprehensive planning process is required. The proposed integrated planning process can facilitate information flow and guide the project's progress. Moreover, the causes of rework in unit production, transportation, and on-site work were analyzed, and work plans to prevent the cause of rework were included. Through this work plan, field rework can be reduced. By using DSM, feedback and reverse information flow are reduced, and the improved information flow can reduce the engineering rework in the design and planning process. Using the proposed integrated process, the work proportions of unit production and on-site work can be determined and can be a starting point for scheduling a modular construction project.

To improve labor productivity in unit production, a model to optimize the modular unit assembly line design was developed. Then, to suggest various unit production schedule alternatives and to consider the trade-off in production line design, the optimization model focuses on MOO. This model can suggest multiple production line design solutions while considering the trade-off between allocated number of workers and the total number of produced units. By using the proposed initialized procedure, the optimization model performance is improved in terms of diversity of the solution set compared to a randomly generated solution set. Based on diversity, the results of the optimization model can embrace various modular construction project schedules.

Then, a crew allocation-based on-site work scheduling method was proposed. Although a significant proportion of work is conducted in a factory, on-site work is conducted to a tight schedule and should consider the unit assembly process. Therefore, the on-site work schedule should be considered in the planning phase. In the on-site work scheduling method, the constraints of activity production rate limit the work schedule optimization and cause idle time. To overcome these constraints, the PSM was used to extend the range of production rates. By extending this range, the on-site work duration and number of workers allocated to on-site work can both be reduced. Moreover, by extending this range, the on-site work schedule can cope with various project schedule alternatives. To validate the proposed scheduling method, a case study was conducted. The results showed that a shorter duration and lower number of workers was required than with the LOB and TACT methods, which were applied to repetitive scheduling methods. However, there is also a trade-off in on-site work scheduling. LOB-based work scheduling can be used in a cost-oriented project, while TACT using the PSM can be used in a time-oriented project. The decision maker can choose the scheduling method according to the project's objective.

6.2 Contributions

By using the scheduling methods in this dissertation, various modular construction schedule alternatives can be generated, and the range of production rates of unit production and on-site work can be extended. The extended production rates mean that project duration can be further shortened, and problems caused by the unit storage yard, on-site labor resource constraints, and tightly scheduled project duration can be alleviated. The scheduling methods focused on reducing labor resource requirements, and the experimental results show a decrease in required labor resources. Therefore, the other contribution is that the scheduling method can alleviate the labor shortage problem in the construction industry. The contributions of this dissertation each stem from a scheduling method, and contributions of each method are as follows:

1) **Establishment of integrated planning process**

Using the proposed planning process, the complexity of information flow in the planning process can be alleviated. Thus, engineering rework in the planning phase can also be reduced. This process includes rework mitigation plans, reducing field rework.

2) **Development of model for unit production line design**

The difference between production line scheduling and unit production line was identified. Then, the optimization problem of unit production line was identified as an NP-hard combinatorial problem of cycle time and resource allocation. To solve this problem, an optimization model and initialization procedure were developed, and the optimization performance was improved in terms of MOO. By using the proposed model, the project manager can adjust unit production duration depending on the project schedule, and production line design can be conducted automatically, which can reduce the duration of production line design.

3) Extension of production rate range of on-site work

By applying the PSM, on-site work duration, idle time, and labor resources can be reduced. Moreover, the production rate of on-site work can be extended, which means on-site work schedules can cope with flexibility. Using the developed simulation model, the on-site work schedule can be evaluated in a controlled simulation environment, and the project manager can choose the work schedule according to the project's objective.

6.3 Limitations

This dissertation proposed scheduling methods for modular construction, but these methods have the following limitations:

1) The scheduling methods in this dissertation focused on flexibility in the project schedule and crew allocation. In terms of flexibility, the scheduling methods only consider adjustment of production rate; therefore, the other constraints that affect flexibility were not considered. In terms of crew allocation, the method is not effective

when the objective of usage of the modular project is not reduced labor resources.

2) The scheduling methods exclude certain works, such as transportation, earth work, and foundation work, which are similar to stick-built construction. The unit production scheduling and on-site work scheduling methods are not integrated, making it difficult to conduct a sensitivity analysis depending on changes to each schedule.

3) To validate the research, case studies were conducted, and the results showed improvement. However, to embrace various modular projects, more case studies are required, such as on high-rise projects, commercial building projects, and projects with various limitations. To complement this research, the scheduling methods should be applied to a real project in the early project phase, and research based on the pilot test should be used to modify this.

4) Finally, when the scheduling method is used in the early project phase, it can be effective. Therefore, an evaluation method to determine adoption of modular construction in the early project phase and investigation of appropriate project delivery methods to

facilitate utilization of the scheduling method are required to improve the efficiency of modular projects.

6.4 Application of Suggested Scheduling Method

To help understanding the application of the proposed scheduling method, an application scenario is described. This scenario is based on the assumptions that 1) the client has an intent to use modular construction from the beginning of their project, 2) to integrate project participants, a delivery method to facilitate this integration, such as IPD, should be used, and 3) project duration is determined. As a first step, the project manager investigates the construction site and then distributes construction site information to project participants, such as architect, unit production manager, transportation manager, and on-site construction manager. The managers have a duration for reviewing the site information. Then, the project manager convenes a meeting to integrate the requirements from each participant and to determine the matters that require attention related to rework in and after the planning phase. Then, to reduce rework, mitigation plans are established through iterative meetings. If the project manager can acquire information of previous modular projects, this information is also reviewed. Then, to assign the requirements to related planning activities and to integrate the rework mitigation plans, the project manager identifies information relationships among activities in the planning phase. Then, the order of activities is rearranged based on the information relationship using DSM. The project manager distributes the planning process, and the participants cooperate with other participants based on the information relationship. The project manager proceeds with the planning process, and then design documentation, unit production, and on-site work planning are suggested as a results of the planning process. The work planning includes activities of unit production and on-site work; thus, unit production and on-site manager can establish each schedule based on the assigned activities. The unit production manager can design the production line using the developed model, and the model can suggest a set of production line design alternatives. The alternatives have different values, such as the numbers of required workers and production durations. Therefore, the production manager can choose a design alternative depending on the project constraints, such as labor resource constraints and on-site work production rates. After unit production duration is determined, the on-site work is also scheduled using the developed scheduling method. The number of required workers and on-site work duration can be estimated using the developed simulation model. Then, unit production and on-site work schedules are integrated to establish the project schedule. If schedule overrun is predicted, the overlapped duration of unit production and on-site work is adjusted. To adjust the production rate, the project manager can choose another production line design and can adjust on-site work production rate using the PSM. By the iterative adjustment of the production rate, a project schedule for modular construction is established. However, when conducting unit production or on-site work, the schedule can be changed. There are various causes related to such change, and it can cause schedule overrun. To prevent overrun, plans to offset the overrun are also prepared. Generally, to cope with the changes, various types of buffers, such as stacking units, adjusting overlapped duration, and assigning idle time, are used. However, the efficiency of the buffers can be different depending on the project; thus, changes in the schedule and buffers should also be considered in the planning phase. The proposed scheduling method does not include the changes occurring after the planning phase, and to improve its applicability, these changes should be included.

Bibliography

AbouRizk, S. M., Halpin, D. W., and Lutz, J. D. "State of the art in construction simulation." *Proc., Proceedings of the 24th conference on Winter simulation*, ACM, 1271-1277.

Al-Hussein, M., Alkass, S., and Moselhi, O. 2001. "An algorithm for mobile crane selection and location on construction sites." *Construction Innovation*, 1(2), 91-105.

Al-Bazi, A., and Dawood, N. 2010. "Developing crew allocation system for the precast industry using genetic algorithms." *Computer-Aided Civil and Infrastructure Engineering*, 25(8), 581-595.

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

Arashpour, M., Wakefield, R., Blismas, N., and Lee, E. 2013. "Analysis of disruptions caused by construction field rework on productivity in residential projects." *Journal of construction engineering and management*, 140(2), 04013053.

Arditi, D., and Albulak, M. Z. 1986. "Line-of-balance scheduling in pavement construction." *Journal of construction engineering and management*, 112(3), 411-424.

Arditi, D., Tokdemir, O. B., and Suh, K. 2002. "Challenges in line-of-balance scheduling." *Journal of construction engineering and management*, 128(6), 545-

556.

Arif, M., Espinal, D., and Broadway, R. S. "Estimating, Planning and Controlling Labor in the Industrialized Housing Factory." *Proc., IIE Annual Conference. Proceedings*, Institute of Industrial Engineers-Publisher, 1.

Asefi, H., Jolai, F., Rabiee, M., and Araghi, M. T. 2014. "A hybrid NSGA-II and VNS for solving a bi-objective no-wait flexible flowshop scheduling problem." *The International Journal of Advanced Manufacturing Technology*, 75(5-8), 1017-1033.

Ashley, D. B. 1980. "Simulation of repetitive-unit construction." *Journal of the Construction Division*, 106(2), 185-194.

Askin, R., and Zhou, M. 1997. "A parallel station heuristic for the mixed-model production line balancing problem." *International Journal of Production Research*, 35(11), 3095-3106.

Austin, S., Baldwin, A., Li, B., and Waskett, P. 2000. "Analytical design planning technique (ADePT): a dependency structure matrix tool to schedule the building design process." *Construction Management & Economics*, 18(2), 173-182.

Banerjee, D., Syal, M., and Hastak, M. 2006. "Material flow-based facility layout analysis of a manufactured housing production plant." *Journal of Architectural Engineering*, 12(4), 196-206.

Becker, C., and Scholl, A. 2006. "A survey on problems and methods in generalized assembly line balancing." *European journal of operational research*, 168(3), 694-715.

Blismas, N., Pasquire, C., and Gibb, A. 2006. "Benefit evaluation for off-site production in construction." *Construction Management and Economics*, 24(2), 121-130.

Blismas, N., and Wakefield, R. 2009. "Drivers, constraints and the future of offsite manufacture in Australia." *Construction Innovation*, 9(1), 72-83.

Blismas, N. G., Pendlebury, M., Gibb, A., and Pasquire, C. 2005. "Constraints to the use of off-site production on construction projects." *Architectural Engineering and Design Management*, 1(3), 153-162.

Boyd, N., Khalfan, M. M., and Maqsood, T. 2012. "Off-site construction of apartment buildings." *Journal of Architectural Engineering*, 19(1), 51-57.

Burati Jr, J. L., Farrington, J. J., and Ledbetter, W. B. 1992. "Causes of quality deviations in design and construction." *Journal of construction engineering and management*, 118(1), 34-49.

Carr, R. I., and Meyer, W. L. "Planning construction of repetitive building units." *Proc., Readings in Cost Engineering*, ASCE, 149-158.

Chan, W.-T., and Hu, H. 2001. "An application of genetic algorithms to precast production scheduling." *Computers & Structures*, 79(17), 1605-1616.

Chen, C., and Tiong, L. K. 2018. "Using queuing theory and simulated annealing to design the facility layout in an AGV-based modular manufacturing system." *International Journal of Production Research*, 1-18.

Chen, C., Tiong, L. K., and Chen, I.-M. 2018. "Using a genetic algorithm to schedule the space-constrained AGV-based prefabricated bathroom units manufacturing system." *International Journal of Production Research*, 1-17.

Cho, K., Hong, T., and Hyun, C. T. 2013. "Space zoning concept-based scheduling model for repetitive construction process." *Journal of Civil Engineering and Management*, 19(3), 409-421.

Chrzanowski Jr, E. N., and Johnston, D. W. 1986. "Application of linear scheduling." *Journal of construction engineering and management*, 112(4), 476-491.

Dawood, N., Ahmed, R., and Dean, J. "Modeling of precast concrete production operations and innovations: A simulation approach." *Proc., Manubuild Conference*.

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. 2002. "A fast and elitist multiobjective genetic algorithm: NSGA-II." *IEEE transactions on evolutionary computation*, 6(2), 182-197.

Dudek, R., Panwalkar, S., and Smith, M. 1992. "The lessons of flowshop scheduling research." *Operations Research*, 40(1), 7-13.

Eastman, C. M., and Sacks, R. 2008. "Relative productivity in the AEC industries in the United States for on-site and off-site activities." *Journal of construction engineering and management*, 134(7), 517-526.

El-Mihoub, T. A., Hopgood, A. A., Nolle, L., and Battersby, A. 2006. "Hybrid Genetic Algorithms: A Review." *Engineering Letters*, 13(2), 124-137.

El-Rayes, K., and Moselhi, O. 1998. "Resource-driven scheduling of repetitive activities." *Construction Management & Economics*, 16(4), 433-446.

El-Rayes, K., and Moselhi, O. 2001. "Optimizing resource utilization for repetitive construction projects." *Journal of construction engineering and management*, 127(1), 18-27.

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

Gibb, A. (2000). "Client’s Guide and Toolkit for Optimising Standardisation and Pre-Assembly in Construction." CIRIA Report CP/75. London: Construction Industry Research and Information Association.

Haas, C. T., Tucker, R. L., and Villalobos, J. (1998). *Multiskilling Labor Strategies in Construction: Implementation of Multiskilling in the Construction Industry*, Construction Industry Institute.

Hammad, A. A., Senghore, O., Hastak, M., and Syal, M. (2003). "Simulation model for manufactured housing processes." *Computing in Civil Engineering (2002)*, 286-297.

Han, S., Al-Hussein, M., Hasan, S., Gökçe, K. U., and Bouferguene, A. "Simulation of mobile crane operations in 3D space." *Proc., Simulation Conference (WSC), Proceedings of the 2012 Winter*, IEEE, 1-12.

Han, S. H., Hasan, S., Bouferguène, A., Al-Hussein, M., and Kosa, J. 2014. "Utilization of 3D visualization of mobile crane operations for modular construction on-site assembly." *Journal of management in engineering*, 31(5), 04014080.

Han, Y.-Y., Gong, D.-w., Sun, X.-Y., and Pan, Q.-K. 2014. "An improved NSGA-II algorithm for multi-objective lot-streaming flow shop scheduling problem." *International Journal of Production Research*, 52(8), 2211-2231.

Hwang, B.-G., Thomas, S. R., Haas, C. T., and Caldas, C. H. 2009. "Measuring the impact of rework on construction cost performance." *Journal of construction engineering and management*, 135(3), 187-198.

Ioannou, P. G., and Yang, I.-T. 2016. "Repetitive Scheduling Method: Requirements, Modeling, and Implementation." *Journal of construction engineering and management*, 142(5), 04016002.

Ipsilandis, P. G. 2006. "Multiobjective optimization in linear repetitive project scheduling." *Operational Research*, 6(3), 255-269.

Ipsilandis, P. G. 2007. "Multiobjective linear programming model for scheduling linear repetitive projects." *Journal of construction engineering and management*, 133(6), 417-424.

Johnsson, H., and Meiling, J. H. 2009. "Defects in offsite construction: timber module prefabrication." *Construction Management and Economics*, 27(7), 667-681.

Johnston, D. W. 1981. "Linear scheduling method for highway construction." *Journal of the Construction Division*, 107(2).

Josephson, P.-E., and Hammarlund, Y. 1999. "The causes and costs of defects in construction: A study of seven building projects." *Automation in Construction*, 8(6), 681-687.

Kim, Y., Han, J., Shin, D., Kim, K., Kim, and Seo, S. 2003. "A Tact planning and scheduling process model for reduction of finishing work duration in building construction projects." *Journal of the Architectural Institute of Korea*, 19(1), 161-167.

Ko, C.-H., and Wang, S.-F. 2011. "Precast production scheduling using multi-objective genetic algorithms." *Expert Systems with Applications*, 38(7), 8293-8302.

Lawson, M., Ogden, R., and Goodier, C. (2014). *Design in modular construction*, CRC Press.

Lawson, R. M., Ogden, R. G., and Bergin, R. 2011. "Application of modular construction in high-rise buildings." *Journal of Architectural Engineering*, 18(2), 148-154.

Lawson, R. M., and Richards, J. 2010. "Modular design for high-rise buildings." *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, 163(3), 151-164.

Lee, D., Kim, D.-S., Kim, G.-H., and Kim, S. 2015. "Time reduction effect of the enhanced TACT method for high-rise residential buildings." *Journal of Civil Engineering and Management*, 1-10.

Lee, J., Park, M., Lee, H.-S., Kim, T., Kim, S., and Hyun, H. 2017. "Workflow dependency approach for modular building construction manufacturing process using Dependency Structure Matrix (DSM)." *KSCE Journal of Civil Engineering*, 21(5), 1525-1535.

Lee, S., Han, S., and Peña-Mora, F. "Hybrid system dynamics and discrete event simulation for construction management." *Proc., Proceeding of the 2007 ASCE International Workshop on Computing in Civil Engineering*, Reston, VA, 232-239.

Lei, Z., Taghaddos, H., Olearczyk, J., Al-Hussein, M., and Hermann, U. 2013. "Automated method for checking crane paths for heavy lifts in industrial projects." *Journal of construction engineering and management*, 139(10), 04013011.

Liu, Y., Dong, H., Lohse, N., and Petrovic, S. 2016. "A multi-objective genetic algorithm for optimisation of energy consumption and shop floor production performance." *International Journal of Production Economics*, 179, 259-272.

Love, P. E., and Edwards, D. J. 2004. "Determinants of rework in building construction projects." *Engineering, Construction and Architectural Management*, 11(4), 259-274.

Love, P. E., Holt, G. D., Shen, L. Y., Li, H., and Irani, Z. 2002. "Using systems dynamics to better understand change and rework in construction project management systems." *International Journal of Project Management*, 20(6), 425-436.

Love, P. E., and Li, H. 2000. "Quantifying the causes and costs of rework in construction." *Construction Management & Economics*, 18(4), 479-490.

Love, P. E., Li, H., and Mandal, P. 1999. "Rework: a symptom of a dysfunctional supply-chain." *European Journal of Purchasing & supply management*, 5(1), 1-11.

Love, P. E., Mandal, P., and Li, H. 1999. "Determining the causal structure of rework influences in construction." *Construction Management & Economics*, 17(4), 505-517.

Lu, N. 2009. "The current use of offsite construction techniques in the United States construction industry." *Seattle, Washington*, 96-96.

Mayer, R. J., Benjamin, P. C., Caraway, B. E., and Painter, M. K. 1995. "A framework and a suite of methods for business process reengineering." *Business process reengineering: a managerial perspective*, 3, 245-290.

Mehrotra, N., Syal, M., and Hastak, M. 2005. "Manufactured housing production layout design." *Journal of Architectural Engineering*, 11(1), 25-34.

Moghadam, M., Al-Hussein, M., Al-Jibouri, S., and Telyas, A. 2012. "Post simulation visualization model for effective scheduling of modular building construction." *Canadian Journal of Civil Engineering*, 39(9), 1053-1061.

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

Murata, T., Ishibuchi, H., and Tanaka, H. 1996. "Multi-objective genetic algorithm and its applications to flowshop scheduling." *Computers & industrial engineering*, 30(4), 957-968.

Nahangi, M., Safa, M., Shahi, A., and Haas, C. T. "Automated registration of 3D point clouds with 3D CAD models for remote assessment of staged fabrication." *Proc., Construction Research Congress 2014: Construction in a Global Network*, 1004-1013.

Nasereddin, M., Mullens, M. A., and Cope, D. 2007. "Automated simulator development: A strategy for modeling modular housing production." *Automation in Construction*, 16(2), 212-223.

Nassar, K. 2011. "Evolutionary optimization of resource allocation in repetitive construction schedules." *Journal of Information Technology in Construction (ITcon)*, 10(18), 265-273.

O'Brien, J. J. 1975. "VPM scheduling for high-rise buildings." *Journal of the Construction Division*, 101(4), 895-905.

Olearczyk, J., Al-Hussein, M., and Bouferguène, A. 2014. "Evolution of the crane selection and on-site utilization process for modular construction multilifts." *Automation in Construction*, 43, 59-72.

Oloufa, A. A., Hosni, Y. A., Fayez, M., and Axelsson, P. 2004. "Using DSM for modeling information flow in construction design projects." *Civil Engineering and Environmental Systems*, 21(2), 105-125.

Park, H. K., and Ock, J.-H. 2016. "Unit modular in-fill construction method for high-rise buildings." *KSCE Journal of Civil Engineering*, 20(4), 1201-1210.

Park, M., Cho, J.-Y., Lee, H.-S., Kwon, S.-K., and Ahn, S.-j. 2012. "BIM Design Management Process Using the Dependency Structure Matrix at the Introduction Phase." *Journal of the Architectural Institute of Korea*, 28(1), 37-45.

Pasquire, C. L., and Gibb, A. G. 2002. "Considerations for assessing the benefits of standardisation and pre-assembly in construction."

PINTO, P. A., Dannenbring, D. G., and Khumawala, B. M. 1981. "Branch and bound and heuristic procedures for assembly line balancing with paralleling of stations." *THE INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH*, 19(5), 565-576.

Rahmandad, H., and Hu, K. 2010. "Modeling the rework cycle: capturing multiple defects per task." *System Dynamics Review*, 26(4), 291-315.

Rahnamayan, S., Tizhoosh, H. R., and Salama, M. M. 2007. "A novel population initialization method for accelerating evolutionary algorithms." *Computers & Mathematics with Applications*, 53(10), 1605-1614.

Reda, R. M. 1990. "RPM: Repetitive project modeling." *Journal of construction engineering and management*, 116(2), 316-330.

Rubinovitz, J., and Levitin, G. 1995. "Genetic algorithm for assembly line balancing." *International Journal of Production Economics*, 41(1-3), 343-354.

Schoenborn, J. (2012). "A case study approach to identifying the constraints and barriers to design innovation for modular construction." Virginia Tech.

Shaked, O., and Warszawski, A. 1992. "CONSCHED: expert system for scheduling of modular construction projects." *Journal of construction engineering and management*, 118(3), 488-506.

Smith, G., and Jirik, T. 2006. "Making zero rework a reality: A comparison of zero accident methodology to zero rework and quality management." *Construction Industry Institute, Research Report*, 203-211.

Smith, R. E. (2011). *Prefab architecture: A guide to modular design and construction*, John Wiley & Sons.

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

Todorovski, M., and Rajicic, D. 2006. "An initialization procedure in solving optimal power flow by genetic algorithm." *IEEE transactions on power systems*, 21(2), 480-487.

Wang, H., Fu, Y., Huang, M., Huang, G. Q., and Wang, J. 2017. "A NSGA-II based memetic algorithm for multiobjective parallel flowshop scheduling problem." *Computers & industrial engineering*, 113, 185-194.

Yamin, R. A., and Harmelink, D. J. 2001. "Comparison of linear scheduling model (LSM) and critical path method (CPM)." *Journal of construction engineering and management*, 127(5), 374-381.

Zou, X., Fang, S.-C., Huang, Y.-S., and Zhang, L.-H. 2016. "Mixed-Integer Linear Programming Approach for Scheduling Repetitive Projects with Time-Cost Trade-Off Consideration." *Journal of computing in civil engineering*, 06016003.

Appendix: Activity Information for Assembly Line Design and Assembly Line Optimization Results

The assembly line optimization in chapter 4, is conducted based on the activity information of modular unit assembly line. In this appendix, the activity information is provided. Then, the production line design optimized with the suggested initialized procedure, also are provided. However, it is impossible to present the all optimization result in this dissertation, the examples which have unique results, are included.

Table A-1. Activity Information on Production Line

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
1	ST1	Wall Stud Installation	40	Sheet Steel Worker	2	Inside	4
2	ST1	Install Insulator to Steel Frame	30	Construction Labor	1	Outside	4
3	ST1	Install Door and Window Frame (Short Side)	40	Window Framer	2	Outside	4
4	ST1	Install Pipe Shaft Frame	10	Metal Worker	1	Outside	4
5	ST1	Corner Floor Concrete Pouring	10	Construction Labor	1	Inside	4
6	ST2	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	20	Joiner	2	Inside	4

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
7	ST2	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	140	Joiner	2	Inside	4
8	ST2	Install Insulator(Glass Wool) to Wall(Long Side)	60	Construction Labor	2	Outside	4
9	ST2	Install Electric Power Distribution Cabinet (Short Side)	5	Electricians	1	Inside	4
10	ST2	Install Wall Pipe (Short Side)	10	Pipefitter	1	Inside	4
11	ST2	Fix Wall Pipe (Long Side)	10	Pipefitter	1	Inside	4
12	ST2	Install Wall Pipe (Long Side)	20	Pipefitter	1	Inside	4
13	ST3	Install Gypsum Board to Inside Wall (Short Side)	80	Joiner	2	Inside	4
14	ST3	Install Cement Board (Long Side)	40	Joiner	2	Outside	4

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
15	ST3	Inside Stud Installation (Bath Room)	10	Joiner	1	Inside	4
16	ST3	Install Insulator(Glass Wool) to Wall(Long Side)	60	Construction Labor	2	Outside	4
17	ST4	Install Insulator(Glass Wool) to Wall(Short Side)	30	Construction Labor	1	Outside	4
18	ST4	Install Cement Board (Long Side)	40	Joiner	2	Outside	4
19	ST4	Install Insulator to Inside Wall	10	Joiner	1	Inside	4
20	ST4	Install Pipe in Pipe Shaft Frame	80	Pipefitter	2	Inside	4
21	ST4	Install Power Outlet Box and Electric Wire	20	Electricians	2	Inside	4
22	ST4	Install Lighting and Outlet Socket	60	Electricians	2	Inside	4

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
23	ST4	Install Stiffening Plate for Fixing Sanitary Fixture in Bathroom	10	Joiner	1	Inside	2
24	ST4	Wrap Water Proof Paper (Long Side)	40	Joiner	2	Outside	4
25	ST5	Install Water Proof Gypsum Board to Bathroom	80	Joiner	2	Inside	2
26	ST5	Install Cement Board (Short Side)	40	Joiner	2	Outside	4
27	ST5	Install Gypsum Board to Inside Wall (Short Side)	40	Joiner	2	Inside	4
28	ST5	Wrap Water Proof Paper (Long Side)	40	Joiner	2	Outside	4
29	ST5	Install Outlet Socket (Short Aisle Side)	20	Electricians	2	Outside	4

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
30	ST6	Install Door	60	Metal Worker	2	Outside	4
31	ST6	Install Window	20	Window Framer	2	Outside	4
32	ST6	Putty Inside Wall	30	Painter	1	Inside	4
33	ST6	Electric Wiring in Ceiling	60	Electricians	2	Inside	4
34	ST7	Install Pipe Shaft Frame Door	20	Metal Worker	2	Outside	4
35	ST7	Transport Steel Frame for Fixing Exterior Wall Panel Bracket	5	Metal Worker	1	Outside	4
36	ST7	Fix the Steel Frame for Exterior Wall Panel	40	Metal Worker	2	Outside	4
37	ST7	Lighting and Outlet Socket Wiring	40	Electricians	2	Outside	4
38	ST8	Install Hanger Bolt for Suspended Ceiling	40	Joiner	2	Inside	4
39	ST8	Install Curtain Box	40	Joiner	2	Inside	4

ID	Station	Work Name	Duration by single worker	Type of Worker	Minimum Required Number of Workers	Location	Max. Number of Workers
40	ST8	Install Carrying Channel for Suspended Ceiling	20	Joiner	2	Inside	4
41	ST8	Install Minor Channel for Suspended Ceiling	20	Joiner	2	Inside	4
42	ST8	Install M-bar for Suspended Ceiling	40	Joiner	2	Inside	4
43	ST8	Install Outlet Socket Cover (Short Aisle Side)	5	Electricians	1	Outside	4
44	ST9	Install Gypsum Board to Ceiling	120	Joiner	2	Inside	4
45	ST10	Wrapping Modular Unit	60	Joiner	2	Inside	4

Table A-2(a). Example of Optimized Production Line Design (Cycle Time:238; Workers:33; Units:39)

Work ID	Sub ID	Work Name	Num. of Workers	Station
1	0	Wall Stud Installation	2	1
2	0	Install Insulator to Steel Frame	1	1
3	0	Install Door and Window Frame (Short Side)	2	1
4	0	Install Pipe Shaft Frame	1	1
5	0	Corner Floor Concrete Pouring	1	1
6	0	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	2	1
7	0	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	2	1
8	0	Install Insulator(Glass Wool) to Wall(Long Side)	1	1
9	0	Install Electric Power Distribution Cabinet (Short Side)	1	1
10	0	Install Wall Pipe (Short Side)	1	1
11	0	Fix Wall Pipe (Long Side)	1	1
12	0	Install Wall Pipe (Long Side)	1	1
13	1	Install Gypsum Board to Inside Wall (Short Side)	1	1

Work ID	Sub ID	Work Name	Num. of Workers	Station
13	2	Install Gypsum Board to Inside Wall (Short Side)	2	2
14	0	Install Cement Board (Long Side)	2	2
15	0	Inside Stud Installation (Bath Room)	1	2
16	0	Install Insulator(Glass Wool) to Wall(Long Side)	2	2
17	0	Install Insulator(Glass Wool) to Wall(Short Side)	2	2
18	0	Install Cement Board (Long Side)	2	2
19	0	Install Insulator to Inside Wall	2	2
20	0	Install Pipe in Pipe Shaft Frame	2	2
21	0	Install Power Outlet Box and Electric Wire	1	2
22	0	Install Lighting and Outlet Socket	1	2
23	0	Install Stiffening Plate for Fixing Sanitary Fixture in Bathroom	1	2
24	0	Wrap Water Proof Paper (Long Side)	2	2
25	1	Install Water Proof Gypsum Board to Bathroom	2	2
25	2	Install Water Proof Gypsum Board to Bathroom	1	2

Work ID	Sub ID	Work Name	Num. of Workers	Station
25	3	Install Water Proof Gypsum Board to Bathroom	1	3
26	0	Install Cement Board (Short Side)	1	3
27	0	Install Gypsum Board to Inside Wall (Short Side)	2	3
28	0	Wrap Water Proof Paper (Long Side)	3	3
29	0	Install Outlet Socket (Short Aisle Side)	1	3
30	0	Install Door	2	3
31	0	Install Window	2	3
32	0	Putty Inside Wall	1	3
33	0	Electric Wiring in Ceiling	2	3
34	0	Install Pipe Shaft Frame Door	2	3
35	0	Transport Steel Frame for Fixing Exterior Wall Panel Bracket	1	3
36	0	Fix the Steel Frame for Exterior Wall Panel	2	3
37	0	Lighting and Outlet Socket Wiring	2	3
38	1	Install Hanger Bolt for Suspended Ceiling	2	3

Work ID	Sub ID	Work Name	Num. of Workers	Station
38	2	Install Hanger Bolt for Suspended Ceiling	2	3
38	3	Install Hanger Bolt for Suspended Ceiling	2	4
39	0	Install Curtain Box	2	4
40	0	Install Carrying Channel for Suspended Ceiling	2	4
41	0	Install Minor Channel for Suspended Ceiling	2	4
42	0	Install M-bar for Suspended Ceiling	2	4
43	0	Install Outlet Socket Cover (Short Aisle Side)	1	4
44	0	Install Gypsum Board to Ceiling	2	4
45	0	Wrapping Modular Unit	1	4

Table A-2(b). Example of Optimized Production Line Design (Cycle Time: 79; Workers: 48; Units: 114)

Work ID	Sub ID	Work Name	Num. of Workers	Station
1	0	Wall Stud Installation	2	1
2	0	Install Insulator to Steel Frame	1	1
3	0	Install Door and Window Frame (Short Side)	2	1
4	0	Install Pipe Shaft Frame	1	1
5	0	Corner Floor Concrete Pouring	1	1
6	1	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	1	1
6	2	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	2	2
7	0	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	2	2
8	1	Install Insulator(Glass Wool) to Wall(Long Side)	1	2
8	2	Install Insulator(Glass Wool) to Wall(Long Side)	1	2
8	3	Install Insulator(Glass Wool) to Wall(Long Side)	1	3
9	0	Install Electric Power Distribution Cabinet (Short Side)	1	3

Work ID	Sub ID	Work Name	Num. of Workers	Station
10	0	Install Wall Pipe (Short Side)	1	3
11	0	Fix Wall Pipe (Long Side)	1	3
12	1	Install Wall Pipe (Long Side)	1	3
12	2	Install Wall Pipe (Long Side)	1	4
13	1	Install Gypsum Board to Inside Wall (Short Side)	1	4
13	2	Install Gypsum Board to Inside Wall (Short Side)	2	5
14	0	Install Cement Board (Long Side)	2	5
15	0	Inside Stud Installation (Bath Room)	2	5
16	0	Install Insulator(Glass Wool) to Wall(Long Side)	3	5
17	0	Install Insulator(Glass Wool) to Wall(Short Side)	3	5
18	0	Install Cement Board (Long Side)	2	5
19	1	Install Insulator to Inside Wall	2	5
19	2	Install Insulator to Inside Wall	1	5
20	1	Install Pipe in Pipe Shaft Frame	1	6
20	2	Install Pipe in Pipe Shaft Frame	1	7

Work ID	Sub ID	Work Name	Num. of Workers	Station
21	0	Install Power Outlet Box and Electric Wire	1	7
22	1	Install Lighting and Outlet Socket	1	7
22	2	Install Lighting and Outlet Socket	1	8
23	0	Install Stiffening Plate for Fixing Sanitary Fixture in Bathroom	2	8
24	0	Wrap Water Proof Paper (Long Side)	2	8
25	1	Install Water Proof Gypsum Board to Bathroom	2	8
25	2	Install Water Proof Gypsum Board to Bathroom	1	8
26	1	Install Cement Board (Short Side)	3	8
26	2	Install Cement Board (Short Side)	2	8
27	1	Install Gypsum Board to Inside Wall (Short Side)	4	8
27	2	Install Gypsum Board to Inside Wall (Short Side)	2	8
28	1	Wrap Water Proof Paper (Long Side)	3	8
28	2	Wrap Water Proof Paper (Long Side)	1	8
28	3	Wrap Water Proof Paper (Long Side)	1	9

Work ID	Sub ID	Work Name	Num. of Workers	Station
29	0	Install Outlet Socket (Short Aisle Side)	1	9
30	0	Install Door	2	9
31	0	Install Window	2	10
32	0	Putty Inside Wall	1	10
33	0	Electric Wiring in Ceiling	2	10
34	1	Install Pipe Shaft Frame Door	1	10
34	2	Install Pipe Shaft Frame Door	1	10
35	0	Transport Steel Frame for Fixing Exterior Wall Panel Bracket	1	10
36	1	Fix the Steel Frame for Exterior Wall Panel	1	10
36	2	Fix the Steel Frame for Exterior Wall Panel	1	11
37	0	Lighting and Outlet Socket Wiring	2	11
38	0	Install Hanger Bolt for Suspended Ceiling	2	11
39	0	Install Curtain Box	2	11
40	1	Install Carrying Channel for Suspended Ceiling	2	11

Work ID	Sub ID	Work Name	Num. of Workers	Station
40	2	Install Carrying Channel for Suspended Ceiling	2	12
41	0	Install Minor Channel for Suspended Ceiling	2	12
42	0	Install M-bar for Suspended Ceiling	2	12
43	0	Install Outlet Socket Cover (Short Aisle Side)	1	12
44	1	Install Gypsum Board to Ceiling	2	12
44	2	Install Gypsum Board to Ceiling	2	13
45	0	Wrapping Modular Unit	1	13

Table A-2(c). Example of Optimized Production Line Design (Cycle Time: 47; Workers: 84; Units: 198)

Work ID	Sub ID	Work Name	Num. of Workers	Station
1	0	Wall Stud Installation	2	1
2	0	Install Insulator to Steel Frame	2	1
3	0	Install Door and Window Frame (Short Side)	2	1
4	1	Install Pipe Shaft Frame	1	1
4	2	Install Pipe Shaft Frame	1	2
5	0	Corner Floor Concrete Pouring	1	2
6	0	Install Fire and Water Proof Gypsum Board to Inside Wall (Long Side)	2	2
7	1	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	2	2
7	2	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	2	2
7	3	Install Fire Proof Gypsum Board to Inside Wall (Long Side)	2	3
8	0	Install Insulator(Glass Wool) to Wall(Long Side)	2	4
9	0	Install Electric Power Distribution Cabinet (Short Side)	1	4
10	0	Install Wall Pipe (Short Side)	2	4

Work ID	Sub ID	Work Name	Num. of Workers	Station
11	0	Fix Wall Pipe (Long Side)	1	4
12	0	Install Wall Pipe (Long Side)	2	5
13	0	Install Gypsum Board to Inside Wall (Short Side)	3	5
14	1	Install Cement Board (Long Side)	2	5
14	2	Install Cement Board (Long Side)	2	5
15	0	Inside Stud Installation (Bath Room)	2	6
16	0	Install Insulator(Glass Wool) to Wall(Long Side)	3	6
17	0	Install Insulator(Glass Wool) to Wall(Short Side)	2	6
18	1	Install Cement Board (Long Side)	2	6
18	2	Install Cement Board (Long Side)	2	7
19	0	Install Insulator to Inside Wall	2	7
20	0	Install Pipe in Pipe Shaft Frame	3	7
21	0	Install Power Outlet Box and Electric Wire	4	7
22	1	Install Lighting and Outlet Socket	4	7
22	2	Install Lighting and Outlet Socket	4	8

Work ID	Sub ID	Work Name	Num. of Workers	Station
23	0	Install Stiffening Plate for Fixing Sanitary Fixture in Bathroom	2	8
24	0	Wrap Water Proof Paper (Long Side)	2	8
25	1	Install Water Proof Gypsum Board to Bathroom	2	8
25	2	Install Water Proof Gypsum Board to Bathroom	2	8
25	3	Install Water Proof Gypsum Board to Bathroom	2	9
26	0	Install Cement Board (Short Side)	3	9
27	0	Install Gypsum Board to Inside Wall (Short Side)	2	9
28	0	Wrap Water Proof Paper (Long Side)	4	9
29	0	Install Outlet Socket (Short Aisle Side)	2	9
30	0	Install Door	2	10
31	0	Install Window	2	10
32	1	Putty Inside Wall	2	10
32	2	Putty Inside Wall	2	11
33	0	Electric Wiring in Ceiling	2	11

Work ID	Sub ID	Work Name	Num. of Workers	Station
34	1	Install Pipe Shaft Frame Door	2	11
34	2	Install Pipe Shaft Frame Door	2	11
35	0	Transport Steel Frame for Fixing Exterior Wall Panel Bracket	1	12
36	0	Fix the Steel Frame for Exterior Wall Panel	3	12
37	0	Lighting and Outlet Socket Wiring	2	12
38	1	Install Hanger Bolt for Suspended Ceiling	2	12
38	2	Install Hanger Bolt for Suspended Ceiling	2	12
38	3	Install Hanger Bolt for Suspended Ceiling	2	13
39	0	Install Curtain Box	2	13
40	0	Install Carrying Channel for Suspended Ceiling	2	13
41	0	Install Minor Channel for Suspended Ceiling	2	13
42	0	Install M-bar for Suspended Ceiling	3	14
43	0	Install Outlet Socket Cover (Short Aisle Side)	1	14
44	1	Install Gypsum Board to Ceiling	2	14

Work ID	Sub ID	Work Name	Num. of Workers	Station
44	2	Install Gypsum Board to Ceiling	2	15
45	0	Wrapping Modular Unit	3	15

國 文 抄 錄

人力資源 配置計劃에 基盤한 工業化 建築工事 工程計劃 方案

미국, 호주, 싱가폴과 같은 선진국의 건설산업은 노동력 부족 문제를 겪고 있으며, 건설산업에 진입하려는 신규 노동자 또한 감소하고 있어 어려움을 겪고 있다. 이는 프로젝트의 공기지연 및 비용 초과 문제로 이어진다. 모듈러 건축은 건설산업의 노동력 부족 문제를 해결하기 위한 효과적인 접근 방법이다. 모듈러 건축은 건축물을 구성하는 유닛의 생산 및 건축물을 완성하기 위한 현장작업으로 구성되어 있으며, 대부분의 작업은 유닛 생산을 위한 제작공장에서 수행되기 때문에 외부 환경 요인으로 인한 영향을 최소화 할 수 있다. 따라서, 제조업의 높은 생산성을 건축 프로젝트에 적용할 수 있으며, 비용, 공사기간, 품질, 안전 측면에서 장점을 갖게 된다. 하지만, 모듈러 건축 역시 건축 방법의 한 종류이기 때문에 노동 집약적이며, 인력 자원을 관리하기 위한 고도의 프로젝트 관리 기술이 요구되지만, 모듈러 건축 프로젝트 관리 지식을 갖춘 전문가의 부족으로 인하여 프로젝트의 비용증가 및 공기지연 문제가 발생한다. 따라서, 작업자의 생산성을 높이고, 짧은 공사기간 동안에 프로젝트를 성공적으로 수행하기 위해서는 인력자원 배치에 기반한 공정계획 방안이 요구된다. 또한, 유닛 생산과 현장 작업이 동시에 수행되는 모듈러 건축의 특성으로

인하여 동시 작업 기간 설정에 따라 공정계획의 유동성이 발생하게 되며, 유동성으로 인하여 프로젝트 공정계획의 복잡성이 증가하게 된다. 이러한 공정계획의 복잡성 문제를 해결하기 위해서는 모듈러 프로젝트를 위한 공정계획 방안이 요구된다. 따라서 본 논문은 모듈러 프로젝트 공정계획의 유동성을 고려한 인력자원 배치 기반 공정계획 수립 방안을 제시하는 것을 연구 목표로 한다. 연구 목표를 달성하기 위해 첫 번째로, 프로젝트 수행 시 발생하는 재작업으로 인한 공정계획의 변경을 줄이고자 모듈러 프로젝트 계획수립을 위한 통합 프로세스를 제안하였다. 제안된 프로세스를 프로젝트에 적용함으로써, 계획단계에서의 정보흐름체계를 개선할 수 있으며 이를 통하여 계획 단계에서의 각 참여자간의 피드백을 줄일 수 있다. 제안된 프로세스를 활용하여 프로젝트 참여자는 유닛 생산 및 현장 작업 계획을 수립할 수 있으며, 수립된 계획은 유닛 생산 및 현장작업을 위한 공정계획의 출발점이 될 수 있다. 유닛 생산 공정계획을 수립하기 위해 유닛 생산라인 디자인을 위한 다목적 최적화 모델이 개발되었으며, 최적화 결과를 활용하여 다수의 유닛 생산 공정계획안을 도출 할 수 있다. 마지막으로 현장작업 공정계획 방안을 제안하였다. 제시된 방안을 활용하여, 작업공간 간섭 및 작업자의 유휴 시간을 줄일 수 있으며, 이를 통하여 공기 단축 및 투입 인력 감축이 가능하다. 본 연구에서 제시하는 유닛 생산 및 현장작업을 위한 공정계획 방안을 활용하여 기존의 공정계획 방안보다 공기 단축 및 인력자원 절감 측면에서 향상된 결과를 도출할 수 있음을 실험을 통하여 검증하였다. 따라서 본 연구의 결과는 건설산업의 노동력 부족 문제를 완화하는데 활용될 수 있으며, 모듈러 프로젝트를 위한 공정계획 수립에 활용될 수 있을 것으로 예상된다. 학술적인 측면에서는, 모듈러 프로젝트

공정계획의 복잡성을 해결하기 위한 모델을 개발하였다는 점에서 본 연구의 의미를 찾을 수 있다. 본 연구의 한계점으로는, 인력자원 외의 다른 자원은 연구 범위에 포함되지 않았다는 것과, 유닛 생산 공정계획 방안에서는 연속 생산방식만을 고려하였다는 점, 모듈러 건축과 기존 건축 방법에서 중복되는 작업은 고려되지 않았다는 점, 유닛 생산 및 현장 작업을 위한 공정계획 방안이 통합되지 않았다는 점이 본 연구의 한계점이라 할 수 있다.

주요어: 모듈러 건축, 인력 자원 배치, 공정계획관리, 유동성, 공업화 건축, 다목적 함수 최적화, 이산사건 시뮬레이션, 의존구조행렬

학 번: 2014-31098 **이름:** 현 호 상

감사의 글

지난 5년간의 연구내용을 본 논문을 통하여 정리하였습니다. 아직 부족하지만 도움을 주신 분들에게 이 글을 통해 감사의 마음을 전하고자 합니다. 먼저, 지금까지 제가 선택한 길을 갈 수 있도록 기다려 주신 부모님께 감사의 인사를 올립니다. 그리고 항상 저를 배려해 주시는 장인어른, 장모님께도 감사의 인사를 올립니다. 부족한 남편을 믿어주는 든든한 반려자이자 친구인 미래, 부모님 곁을 지켜주는 동생 지혜, 항상 아빠를 응원해 주는 서하와 서진이에게도 고맙다는 말을 하고 싶습니다.

지금의 결실을 맺을 수 있도록 연구실이라는 보금자리를 내어주시고 아낌없는 지도와 격려를 해주신 이현수 교수님과 박문서 교수님께 감사의 인사를 드립니다. 앞으로도 교수님들께서 주신 가르침을 밑거름 삼아 더 나은 연구자가 될 수 있도록 노력하겠습니다. 그리고 바쁘신 일정에도 불구하고 논문을 지도해 주시고 심사에 참여해 주신 지석호 교수님, 안용한 교수님, 김현수 교수님께도 감사의 인사를 드립니다.

2년 동안의 석사과정과 5년 동안의 박사과정을 연구실에서 보내면서 연구실 동료들에게 많은 도움을 받았던 것 같습니다. 든든한 동료이자 선배였던 이정훈 박사, 많은 조언을 해주었던 이광표 박사와 황성주 교수, 권병기 박사, 정민혁 박사에게 감사의

인사를 전합니다. 또한, 모듈러 과제를 함께 수행하면서 많은 도움을 준 김민정, 이두완, 최원규, 김주호, 박찬용, 안수호, 정길수 연구원에게도 감사의 인사를 전합니다. 모든 연구원들에게 다 감사의 인사를 전할 수는 없지만, 항상 건설기술연구실 연구원들에게 도움이 될 수 있는 사람이 되고자 노력하겠습니다.

또한, 많은 도움을 주신 모듈러 연구단 연구원 분들에게 감사의 인사를 드립니다.

두서없이 감사의 글을 쓰다 보니, 도움을 주신 모든 분들에게 감사의 마음을 표할 수 없는 것이 죄송스러울 따름이며, 앞으로도 도움을 줄 수 있는 사람이 될 수 있도록 노력하겠습니다.

감사합니다.

2019 년 8 월 현호상 올림