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Resource and Sequence Optimization Using Constraint Programming in Construction Projects

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Abstract: Construction projects are large-scale projects that require extensive construction costs and resources. Especially, scheduling is considered as one of the essential issues for project success. However, the schedule and resource management are challenging to conduct in high-tech construction projects including complex design of MEP and architectural finishing which has to be constructed within a limited workspace and duration. In order to deal with such a problem, this study suggests resource and sequence optimization using constraint programming in construction projects. The optimization model consists of two modules. The first module is the data structure of the schedule model, which consists of parameters for optimization such as labor, task, workspace, and the work interference rate. The second module is the optimization module, which is for optimizing resources and sequences based on Constraint Programming (CP) methodology. For model validation, actual data of plumbing works were collected from a construction project using a five-minute rate (FMR) method. By comparing actual data and optimized results, this study shows the possibility of reducing the duration of plumbing works in construction projects. This study shows decreased overall project duration by eliminating work interference by optimizing resources and sequences within limited workspaces.

Keywords: Schedule Management, Resource Optimization, Resource-constrained Project, Construction Project

1. INTRODUCTION

Scheduling has been known as one of the most essential issues to be considered in construction projects. To achieve successful scheduling, eliminating hindering factors of work continuity is critical such as work interference and resource idle time. Especially in high-tech construction projects, the schedule and resource management are challenging to conduct in high-tech construction projects including complex design of MEP and architectural finishing which has to be constructed within a limited workspace and duration [1]. For example, project delay such as resource idleness and waiting for preceding resources to finish previous work in the same workplace occurs due to up-and-down simultaneous operation and material delivery delay since the complexity of work increases as the project progresses [2]. Due to these reasons, work interference among labor crews occurs more frequently than other construction projects, which cause failure to secure work continuity, leading to consecutive schedule delays.

In order to solve such issues, previous studies have conducted resource-constrained optimization, known as resource-constrained scheduling problems [3]. However, these studies have difficulties validating the model since they suffer a severe lack of resource productivity data. Lack of data could be crucial for models to be applied to the actual projects since most schedule calculations are based on assumptions. Therefore, we propose resource and sequence optimization methods using constraint programming based on actual productivity data in this study.

2. LITERATURE REVIEW

2.1. Workspace Interference

Construction project scheduling problems have been a decisive but obligatory task for both contractors and researchers in the construction field [4]. Even though it can be easily solved in some cases, most construction projects undergo difficulties in retaining resource availability, including insufficient labor, equipment and workspace. Workspace is considered a renewable resource until planned works in the same workspace are completed. However, if two or more works are occupied in the same workspace, it could lead to various problems in general, such as conflict on workflow, unnecessary labor idle time, and safety problems [5]. Especially in projects which include up-and-down simultaneous works in a workspace with high ceilings, safety problems should not be ignored, such as falling objects and falling from height [6].

Hence, previous studies have established models to solve resource and workspace constraints. This kind of model development methodology has been studied for decades, known as the Resource-Constrained Project Scheduling Problem (RCPSP). However, these studies lack real-life productivity data collection, leading to difficulties applying developed models to real projects. Therefore, the authors have collected productivity data from the case study using a five-minute rating method.

2.2. Constraint Programming

Scheduling optimization considering work interference has to be performed to improve work continuity. However, the complexity of optimization problems increases because the project schedule system is more complex as the project size increases. Constraint programming (CP) is a methodology for solving these complex optimization problems [3,7,8]. CP provides the most feasible solution among the alternatives satisfying the constraints for a given problem. Therefore, it is important to model the constraint to solve a given problem.

Generally, the primary constraint in project scheduling is a resource, such as labor and equipment. However, in construction projects, a workspace can be an important constraint. When the same workspace is occupied by activities simultaneously, work interference occurs, which leads to the discontinuity of activity and resource utilization. Previous studies have suggested various models to optimize the activity precedence [1,4]. However, there are various reasons for workspace conflict, such as safety management, inspections, and material storage, not only activity interference. Reflecting all these factors, the model becomes complicated and hard to its practical application.

Therefore, this study introduces the work interference rate concept, which means the probability of interference occurrence. The work interference rate is measurable by productivity measurement methods such as a five-minute rating. To this end, the proposed concept makes the model practical and easy to reflect the characteristics of the project. Thus, the authors develop a constraint programming-based resource and work sequence optimization model, including the work interference rate concept. The detailed modeling process is explained in the next chapter.

3. MODEL DEVELOPMENT

This chapter describes the model development process for schedule optimization considering work interference. First, we propose the components and the data structure of the schedule model. Secondly, the modeling concept of constraint design for optimization is described.

3.1. Components of Schedule Model

For constraint programming based on resource and work sequence, defining variables for each resource is necessary. Each task in the schedule model has a fixed duration and requires reuseable resources to progress. These reusable resource variables have finite limits; thus, if a specific type of resources required to progress a task is insufficient, the constraint system will delay the start of the task until the resource is available. The schedule model developed in this study consists of labor, task, workspace, and work interference rate variables. The description of each variable is explained in the next section.

3.1.1 Labor, Workspace, and time

Every task has labor, workspace, and time variables. Labor and workspace variables are allocated to task variables. Each variable respectively means labor type who perform the task and the specific location where the task is performed. The time variable consists of the start time, finish time, duration, and interval variable. The interval variable is the main idea of the schedule model for CP, which has a start time, finish time, and duration like a time variable. The role of the interval variable is to represent the non-fixed duration when the task is subject to optimization. Through the interval variable, a modeler can set constraints of the task, such as labor capacity and workspace interference. After optimization, a task variable is updated with the interval variable components. Table 1 shows the data type and detailed description of each variable.

Table 1. The main variable of the schedule model for constrained programming

Component	Variable	Descriptions
Interval	selected	Whether the interval is an optimal solution
	start time	Start time of interval variable
	duration	Duration of an interval variable
	finish time	Finish time of interval variable
Task	interval list	Interval alternatives of task
	Workspace	Workspace where task performed
Workspace	num_section	Number of sections in a workspace
	quantity	Quantity assigned to a workspace
Labor type	productivity	Productivity of labor type

3.1.2 Work Interference Rate and Duration

Work interference rate (WIR) indicates interruption probability during a task due to various causes, such as waiting for inspection and unavailable workspace occupied by other activities, while work interference duration (WID) indicates the duration of the work interference. In our schedule model, WIR decides the number of dummy tasks. A dummy task means interruption, which is created as a predecessor of the target task before optimization. The target task is randomly selected as much as WIR. After the creation of the dummy task, it is treated as a task with WID. It means constraint of task is adopted in dummy tasks. Through this concept, the model can optimize the schedule considering task interruption. WIR and WID values can be measured from actual productivity data.

3.2. Constraint Design

The constraint system in this study is composed of two major types of constraints, precedence constraint, and resource constraint. While precedence constraints are for establishing the network logic of each task, resource constraints are for the allocation of labor and workspace per each task that is required to be processed. The modeling concept of each constraint is described in the section below.

3.2.1 Precedence Constraint

The precedence constraint refers to the precedence relationship between each task of the whole schedule. This constraint is for restricting successor task to start only if predecessor task that logically related to finishes. The concept of precedence constraints with the finish-to-start relationship is represented by

$$Precedence\ Constraint\ (FinishTime_p, StartTime_s), \forall (p,s) \in D \ldots$$

where D denotes the set of every paired tasks that is ordered as tasks (p,s) in precedence. Through the precedence constraints, the end time of the predecessor task must be less than the start time of the successor task.

3.2.2 Labor Constraint

Labor constraint exists due to the total labor put into the project by labor type. Therefore, the total number of labor crews cannot exceed the capacity at a specific time. To set constraints, we denoted the set of tasks performed by labor type i as T_i, and the set of labor types in the schedule model is represented as L. The concept of labor constraint is represented by

$$Labor\ Constraint\ (S_{ij}, d_i, N_{ij}), \forall i \in L, \forall j \in T_i$$

where S_{ij} denotes the set of every interval variable of a task in T_i, d_i denotes the total number of labor type i in the schedule model, and N_{ij} denotes the number of labor type i which is required to perform task j. Therefore main concept of labor constraint is the sum of the N_{ij} of the tasks, which cannot exceed d_i at any given time.

3.2.3 Workspace Constraint

Multiple tasks allocated to the same workspace cannot work at the same time due to a workspace conflict. Likewise, the interval variable, including tasks allocated to the same workspace, cannot exist simultaneously. Therefore, it is essential to apply constraints that make interval variables do not overlap. Thus, workspace constraint refers to the impossibility of simultaneous operation between interval variables. The concept of workspace constraints are represented by

$$Workspace\ Constraint\ (S_i), \forall i \in \{1,2,3,4,\ldots,n\}$$

where S_i denotes the set of interval variables of task performed in workspace i, and n denotes the number of workspaces in the schedule model. Through the workspace constraints, every interval variable in S_i cannot overlap in simulation time.

4. CASE STUDY

The case study was conducted for the optimization tool to analyze work interference. The case is a part of the manufacturing factory construction project, and the work type is plumbing work. First, labor crew productivity data were collected by the five-minute rating method. Based on the data, work interference rate and duration were calculated. Then, schedule optimization was performed applying the measured data. Finally, the authors suggest the implication by comparing the optimal schedule with the performance schedule. The process of the case study is shown in Figure 1.

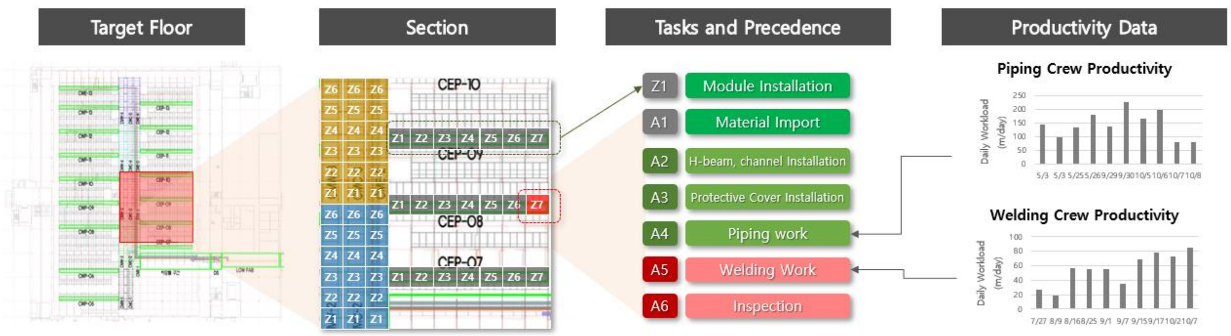

Figure 1. Process of case study

4.1 Case Description

In the case study, the specified floor was suffering from overwhelming resources with the limited schedule provided. Since multiple construction works, such as module installation, electrical, mechanical, and plumbing, were carried out simultaneously on the same floor, interference among works was inevitable. Especially, plumbing works were scheduled from start to finish of the whole master schedule of the floor. Therefore, elimination of work interference of plumbing works is considered a key point to schedule optimization of the entire project.

The plumbing work for the corresponding floor is divided into three main sections, the main module, the eastern side of the lateral module, and the western side lateral module. When the module is lifted and installed, other crews begin working on the module's top side, including plumbing crews on the bottom side of the module. In this work, two crews performed the plumbing work. While each crew is formed as one technician and two assistants, the piping crew works for lifting, settling, and fixing works, and the welding crew mainly weld pipes.

4.2 Data Collection

For constraint design, it is necessary to collect actual productivity data of plumbing works. In this case, the authors chose a five-minute rating (FMR) method to collect data since FMR methodology is well known for collecting productivity data for each labor [9]. Therefore, the authors have discussed and defined activities with actual welding specialists involved in the case project before measuring FMR data. After defining activities of welding works, we have collected 30 days of plumbing work productivity data.

We have compared planned schedule/resource data with FMR data to analyze actual WIR. Since FMR data collect the activities of each crew every five minutes, we have also checked work interference occurrence. Therefore, the authors have analyzed WIR to be 30.74% on plumbing work for the case study, which will be applied later in the model experiment.

Before commencing the experiments, the authors have derived the actual expected duration by analyzing the remaining duration of the plumbing work. With this process, actual duration data samples were extracted. The actual calculated duration of plumbing work is 125 days total, including overtime. This calculation does not include non-work hours or days, which means one day translates into 24 hours specifically.

The proposed model was implemented using Google OR-Tools, a representative tool for CP problems [10]. OR-Tools is a proven tool in numerous studies to deal with CP problems in various research fields [11].

4.3 Results

This section illustrates the experiments to evaluate the proposed model's performance by comparing the actual and sequence optimized schedules with and without WIR. In actual productivity data, the resource input of the welding crew varies from one to nine at maximum. Therefore, the authors have conducted optimization experiments with averaged resource input to be five of the welding crew number for the appropriate comparison results. Table 2 shows the resource input and total work duration of each schedule.

Table 2. Sequence Optimization Results

Description	**Actual Schedule**	**Optimized Schedule (w/o WIR)**	**Optimized Schedule (w/ WIR)**
Total Work Duration (days)	125	111	112
Number of Welding Crews	1-9 (varies)	5	5
Number of Piping Crews	12	12	12
Existence of Idle resources	Yes	No	No

The experiment result of the proposed model's optimized schedule shows that plumbing work would take 111 days without WIR. This result indicates that work continuity is secured for 111 days, the actual duration is shortened by 14 days. With WIR applied, 112 days were derived, which is only a 1-day delay from the optimized plan, which is not much different from the result without WIR. This is because the proposed model has reallocated potential idle resources caused by work interferences to other sections to catch up with the project schedule. Since authors used WIR to express tasks that cause work interference, it is possible for project managers to find alternative workspaces to reallocate idle resources using result of proposed model when work interference occurs in actual project.

In addition, this study performed a sensitivity analysis to explore better resource planning compared to the actual schedule. For the analysis, the authors have regulated the number of each crew to examine the difference in performance. As a result, Figure 2 shows that increasing welding crew number decreases total duration. However, it also reduces the degree of reduction. An analysis result has shown that change of piping crew size does not have as much impact as welding crew size for the piping crew. This sensitivity analysis result shows that the proposed model can help project managers make decisions for adjusting the input of resources according to the project's circumstances.

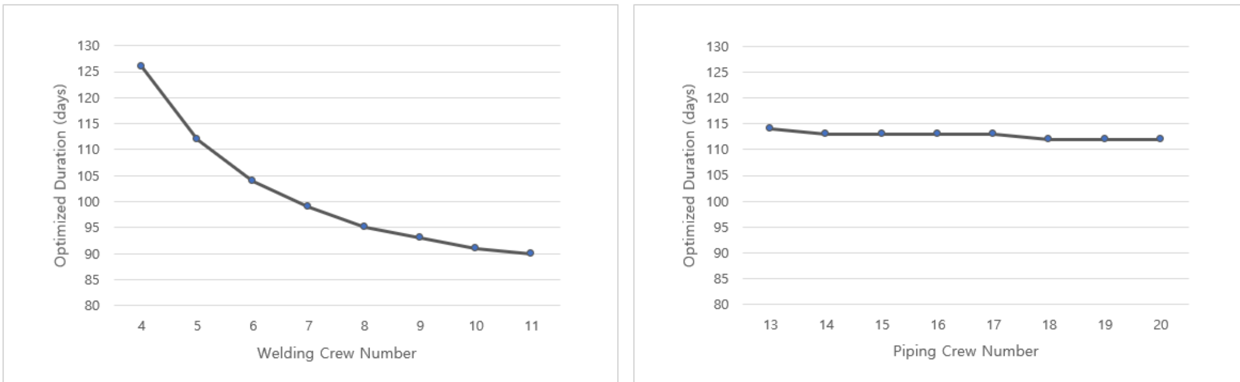

Figure 2. Sensitivity Analysis of Welding Crew (left) and Piping Crew (right)

5. CONCLUSIONS

In this study, the authors have proposed a resource and sequence optimization model using constraint programming in construction projects. By applying the proposed CP model in the case study with actual productivity data, our model allows schedule optimization by a change in activity sequence and resource input. However, since uncertainty in the actual construction site cannot be ignored, continuous update of input data such as resource, duration, and work plan changes to the proposed model is necessary.

This research provides an RCPSP model that requires actual productivity data. Thus, the practicality of the model is very high. Therefore, applying optimized results for forthcoming projects is considered to be effective. This study provides a flexible constraint programming-based resource and work sequence optimization model, which means that input data could be easily modified to derive different results without rebuilding the model. Also, the proposed model can benefit from other types of construction sites which include high complexity of work sequence and vice versa.

The main limitation of the research is that the proposed model does not consider the change in the productivity of labor depending on the work condition. Also, since collected data is based on actual measurement by humans, automated measuring using artificial intelligence-based technology is necessary to collect data from all types of work. In addition, through the practical application of the method proposed in this study, it is necessary to analyze the actual productivity improvement effect and conduct a study to improve site applicability.

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