Formwork Productivity Analysis Model for Cost-efficient Equipment Operations

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ABSTRACT: In the tall building construction, the slab formwork largely impacts on construction cost. Because productivity of a slab formwork is influenced by a number of and the efficiency of equipment, using the equipment-based construction method, an appropriate equipment input planning is crucial for the productivity. Meanwhile, the general equipment input planning is conducted by intuition based on experience due to the lack of equipment productivity data. Thus, this study develop a simulation model to analyze table formwork productivity and to propose an optimum equipment input plan that reflects the construction process, based on the full consideration of the economic factors. This study developed a simulation model by using CYCLONE and the data for the model was collected by measuring the duration of each unit activity in the tall building where table forms were applied. It is expected that a simulation model helps users to make better decision on the equipment input planning of slab formwork.

Keywords: Slab formwork; Productivity; Simulation; CYCLONE

1. INTRODUCTION

Formwork is a crucial process in tall building construction projects, where it accounts for 25% of the total construction period and 10–15% of the overall cost [1] [2]. In advanced countries such as Canada, it is highly recommended that table forms are used during slab formwork processes to increase productivity [3]. Indeed, the table formwork method is applied widely in tall building construction projects.

The table formwork method is an equipment-oriented construction method that is focused on the equipment input plan. If insufficient equipment is available, the installation and stripping work are hindered and the formwork productivity is reduced. However, the efficiency of the operation will be undermined by excessive waiting times if too much equipment is available and the overall cost will increase. Therefore, equipment input planning has major effects on productivity and the formwork cost.

Equipment planning for table formwork is generally done based on managers' experience and intuition. They determine the operational requirements based on their experience, the proportions of the slab area, and the number of table form units. However, this traditional method has some limitations. In particular, it is impossible to accurately forecast productivity while also considering the simultaneous working and waiting times required for equipment. This tends to result in excessive equipment input on construction sites.

Simulation methods can solve these problems. Simulation methods make it possible to construct a model that can forecast the processing time and waiting time, thereby facilitating the design of equipment provision plans by using the production analysis results as the objective standards.

The aim of this study was to develop a model using the CYCLONE technique to analyze table formwork productivity and to propose an optimum equipment input plan that reflects the construction process, based on the full consideration of the economic factors. The results of this study are expected to make a practical contribution that supports real-world equipment provision planning during table forming.

2. EQUIPMENT FOR TABLE FORMWORK

2.1 Shifting Trolley

A shifting trolley is a power train used for the horizontal shifting of table forms (Fig. 1). A trolley is placed below the lower center of the mass to support the table forms, which facilitates their movement to target locations. Trolleys also support the forms when they are installed or stripped. Table forms can be shifted, elevated, or lowered automatically by one member of staff moving a single table form unit. The process is operated automatically, which helps increase the cost effectiveness and productivity.

Figure 1. Shifting Trolley[4]

Figure 2. Lifting System[4]

2.2 Lifting System

Automatic lifting systems are used to lift table forms without the requirement for tower cranes (Fig. 2). The system lifts the table forms by placing them on a deck and moving the deck to the target floor. The elevation and lowering of the deck are operated automatically by calling units inside the slab. The lifting system can raise itself using its hydraulic system. The lifting system helps to reduce the amount of lifting that requires cranes. Avoiding the use of tower cranes also makes the lifting work safer and faster.

3. CYCLONE MODELING

3.1 Project Overview

This study analyzed the processes involved in table forming to build simulation models. Thus, we measured the resource and time requirements of a construction project where table forming was used. The study focused on a construction site in Busan, Korea, which comprised a high-rise office building with 63 floors and three basement levels. We investigated the table formwork processes via an interview with the manager and through measurements. We measured the volume of resources used and the duration of the work activities.

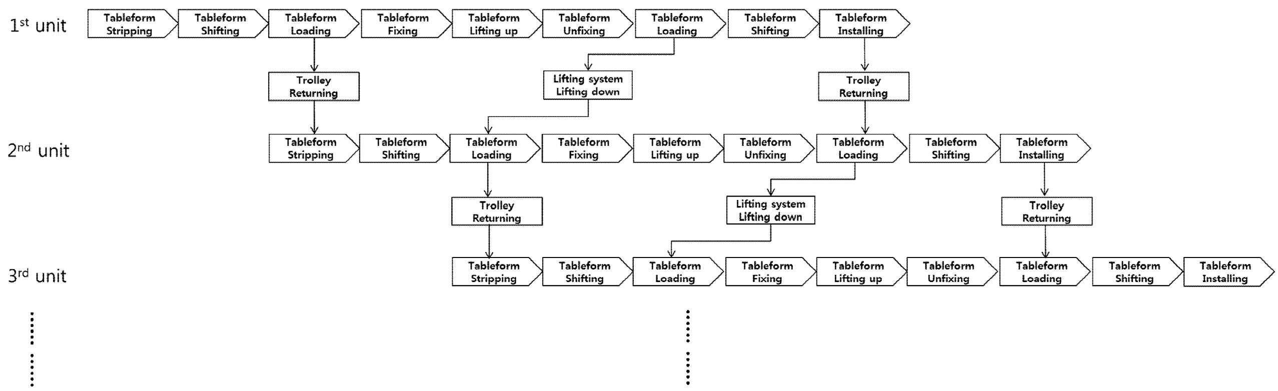

Figure 3. Process of table formwork

3.2 Analysis of the Table Formwork Process

The processes involved in table forming can be divided into three main phases: stripping, lifting, and installation. In the first phase, the table form is stripped and shifted to the lifting spot using a shifting trolley. The table form is lifted and then shifted to the installation spot. Further table form units are disassembled, lifted, and installed in the same manner, until the overall slab formwork process is complete. Figure 3 shows the overall process in detail.

As shown in Figure 3, the table form process requires a consideration of the equipment waiting time and simultaneous operations, because the lifting process coincides with the shifting of the trolley before the next unit is stripped.

3.3 CYCLONE Modeling of the Table Formwork

CYCLONE modeling was used to build a simulation model of the table form process. The CYCLONE method was selected as the best modeling method for the present study because it can reflect the effects of delays caused by resource availability when forecasting productivity [5].

We defined the overall process from stripping work to installation as a unit cycle. The details of the final simulation model, which is shown in Figure 4, are as follows.

(1) Node 2 refers to a stripping phase that requires a stripping crew and a trolley.

(2) Nodes 6–8 refer to a shifting phase before lifting. After a table form is loaded, the trolley moves to the lifting system where it unloads the table form at the lifting location, before moving back to the stripping spot for the next process. A trolley is involved in all of the processes in this phase.

(3) Nodes 11–14 describe a table form lifting phase. The lifting system receives the target table form, which is fixed to the lifting system. It lifts the deck and unloads the table after unfixing it from the deck, before moving downstairs for the next lifting operation. A lifting system is required by all of the processes in this phase.

(4) Nodes 17–20 show a shifting phase during the installation of the target table form. After the table form is loaded, the trolley moves to the installation spot and then it moves back to the lifting deck for the next operation after the installation is complete. A trolley is involved in all of the processes in this phase.

(5) Node 23 is the installation phase. An installation crew and a trolley are required for the installation operation.

3.4 Input Data

All of the resource inputs required for the table formwork were identified during a field investigation. The inputs are shown in Table 1.

Table 1. Resource input data

Resource type	Resource	Amount of resource
Material	Table form	51 table units
Labor	Stripping crew	1 crew
	Installation crew	1 crew
Equipment	Trolley for Stripping(A1)	1 each
	Trolley for Installing(A2)	1 each
	Lifting system (B1)	1 each

We found that 51 table form units were brought into the construction site, which involved one stripping crew, one shifting trolley for stripping(A1), one lifting system(B1), another shifting trolley for installation(A2), and one installation crew. All of the resources and their values were entered into the simulation.

The duration of each unit process was determined based on interviews and the field investigation results. The durations are shown in Table 2.

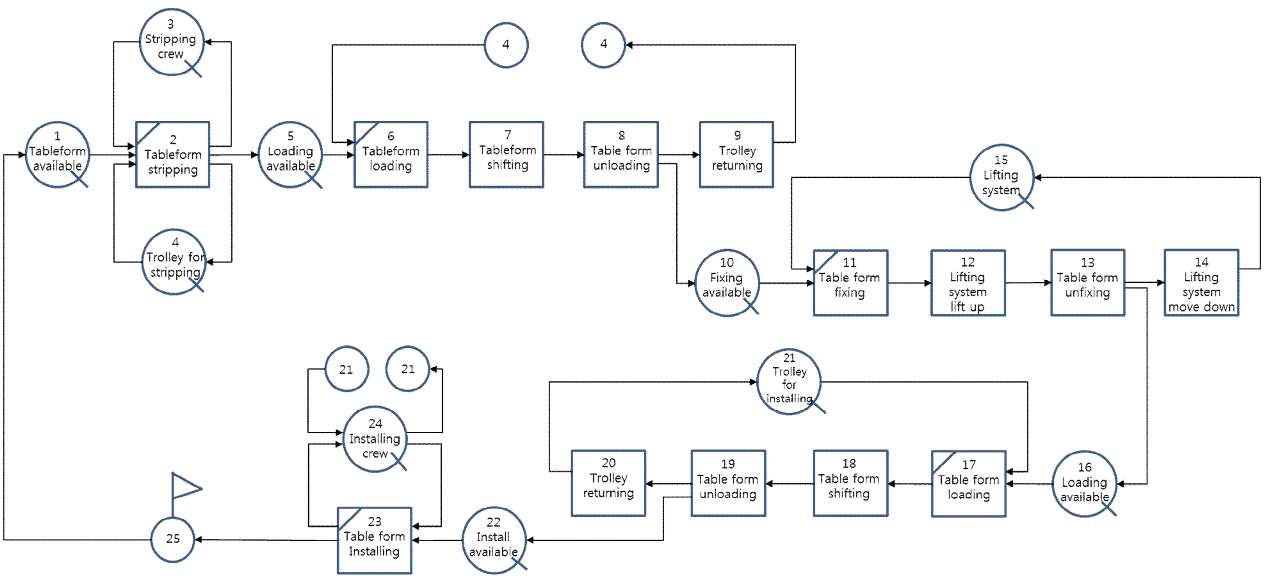

Figure 4. CYCLONE model of table formwork

The durations of stripping and table form installation were calculated by measuring the duration of each operation, which were inputted with a triangular distribution. The measurements showed that the unit processes for loading, unloading, lifting, tying, and untying a table form had almost fixed durations with little variation. We defined the durations of those operations as deterministic values in the simulation.

Table 2. Duration input data

Node	Work task	Duration(min)		
		Min	Mean	Max
2	Table form stripping	1	2.24	3.83
6	Table form loading	0.1		
7	Table form shifting	2.66		
8	Table form unloading	1		
9	Table form returning	2.66		
11	Table form fixing	0.5		
12	Lift system lifting up	1		
13	Table form unfixing	0.5		
14	Lift system moving down	1		
17	Table form loading	1		
18	Table form shifting	2.66		
19	Table form unloading	0.1		
20	Table form returning	2.66		
23	Table form installing	3.65	4.88	6.33

The travel time for table forms differed according to their size and the distance moved, so we calculated the average shifting time for all table form units and entered their deterministic values. The mathematical equation used for the calculation was Eq. (1).

$$T_{shift} = \frac{\sum_{i=1}^{n}(\Delta x_i + \Delta y_i)}{V_{trolley} \times n} \quad (1)$$

Where,
T_{shift} = average duration of table form unit shifting;
$V_{trolley}$ = velocity of shifting trolley(10m/min);
Δx_i = x distance between center of lifting system and center of table form unit i;
Δy_i = y distance between center of lifting system and center of table form unit i; and
n = the number of table form units.

The shifting distance for a table form was calculated by adding the horizontal and vertical distances from the central point of each unit relative to that of the lifting system. The average shifting time for a table form unit was also calculated by summing the distance for all units and dividing the sum by the velocity of the shifting trolley and the number of units.

4. RESULTS

4.1 Productivity Analysis

In the simulation test, we conducted a simulation task 1000 times to ensure the convergence of the productivity values. The values are shown in Table 3. The total duration for 1000 cycles was 11,795 minutes and each table form unit required 11.8 minutes, with a productivity of 0.0848 cycle/min. Thus, the overall duration for the target construction site using 51 units was 589.75 minutes, where the resources detailed above were utilized.

Table 3. Result of the productivity analysis

Total simulation time(min)	Cycle number	Productivity Per time unit (cycle/min)	Cycle time (min)
11795.0	1000	0.08478	11.80

4.2 Sensitivity Analysis

We conducted a sensitivity analysis to analyze the productivity depending on the equipment availability. We analyzed the changes in productivity when the equipment was changed. The equipment selected for the analysis comprised a trolley for stripping, a lifting system, and a trolley for installation. The leasing costs for the equipment were also used to calculate the changes in the cost for different combinations of equipment. The leasing fees for the equipment are shown in Table 4 and the sensitivity analysis results are shown in Table 5.

Table 4. Lease fee of equipment

Equipment	Lease fee per month (won)	Period (month)	Total lease fee (won)
Shifting trolley	450,000	18	8,100,000
Lifting system	7,000,000	18	126,000,000

Table 5. Result of the sensitivity analysis

A1	B1	A2	Productivity (cycle/min)	Total duration (h)	Total cost (won)
1	1	1	0.0849	10.03	142,200,000
1	1	2	0.1125	7.56	150,300,000
1	2	1	0.0848	10.02	268,200,000
1	2	2	0.1121	7.58	276,300,000
2	1	1	0.0856	9.93	150,300,000
2	1	2	0.1698	5.01	158,400,000
2	2	1	0.0857	9.92	276,300,000
2	2	2	0.1702	4.99	284,400,000

According to the sensitivity analysis, the productivity was highest (0.1702 cycle/min) when there were two trolleys for stripping, two lifting systems, and two trolleys for installation. The slab formwork process lasted 4.99 hours. However, the combination of equipment was determined only to ensure the optimum productivity, with no consideration for the economic feasibility. In practical applications, the appropriate combination should be selected based on the economic feasibility.

According to the field investigation and interviews, the slab formwork process required for a single floor accounted for less than 8 hours over 4 days. The most economical combination was one disassembly trolley, one lifting system, and two installation trolleys. The productivity with this combination was 0.1125 cycle/min and the slab formwork process required 7.56 hours, so this combination was the best in terms of economic feasibility.

5. CONCLUSION

This study developed a model using the CYCLONE technique to analyze slab formwork productivity during table form construction. The analysis was based on practical data collected during field investigations of a table form-based construction project. Our simulation study determined the optimum equipment input plan by analyzing the productivity and costs of different combinations of equipment.

The findings and suggestions of the present study are expected to make a practical contribution to the selection of the most economical equipment allocations during table formwork-based construction projects.

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