Simulation-based Planning Model for Table Formwork Operation in Tall Building Construction

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Abstract

Operation planning for table formwork using a crane-independent lifting system (CLS) is a crucial factor affecting productivity for formwork in tall building construction. Inappropriate heuristic operation plans are likely to increase work duration because of temporarily displaced stacks of table forms, and may also increase costs because of excessive use of equipment. The authors propose a simulation-based operation planning model for table formwork for efficient operations in tall building construction. By optimizing the shifting sequence of table forms and the location of the CLS in a case study, the proposed model reduced working hours for table forms by 6.62\% from the working hours derived by a heuristic approach. Furthermore, the derived alternatives reduced working hours by a maximum of 45\%, depending on the number of trolleys used. This study can be utilized for informed decision-making by construction workers in tall building construction while selecting the optimal operation plan for table forms by considering project cost and schedule.

Keywords: operation planning; simulation; pathfinding; table formwork; tall building construction

1. Introduction

In tall building construction, automated and equipment-driven methods are suggested as feasible alternatives to increase productivity in response to the decrease of skilled labor\(^1\). Especially, the formwork method with less manual operation can largely facilitate a reduction of the cycle time for structural framework. Thus, an equipment-driven table formwork method with a crane-independent lifting system (CLS) has been applied to the horizontal formwork of various tall building constructions\(^2\).

An efficient operation plan for table formwork construction using CLS is a crucial factor affecting the productivity for formwork. Table formwork using CLS requires trolleys to move stripped table forms to the CLS on the stripping floor and to move the table forms from the CLS onto the installation floor. Additional resource inputs and operation plans for utilization of trolleys influence productivity by reducing waiting time between formwork activities. In addition, because installed table forms may act as obstacles to shifting other table forms, the shifting sequence of table forms affects the total distance moved and the time required for the process. Thus, reasonable decision making for efficient operation of the equipment-driven table formwork method is crucial.

Operation planning for the table formwork method has previously been conducted using heuristic approaches by a construction supervisor who relies on experience. As the decision maker, the supervisor may have planned the operation on the basis of previous construction projects, or may have based the entire operation plan for table forms on the average working hours required for each unit area of construction\(^3\). However, such empirical equipment plans do not consider either the geometrical or structural dimensions of a construction project, and inadequately calculated operation time per unit table form results in a waste of both resources and construction time\(^4\). Furthermore, the heuristic method has limitations in making optimal selection among numerous alternatives for shifting table forms. Current methods are prone to selecting inappropriate alternatives that cause increased numbers of table forms to be temporarily displaced because of unavailability of installation resources and increased work duration because of table forms being moved increased distances.

In this study, the authors propose a simulation-based operation-planning model for table formwork for...
selection of an optimal operation plan. The simulation model is established by exploiting discrete event simulation for table formwork using an independent CLS. The working time for each alternative is calculated by considering the operation method and the number of trolleys employed as decision variables. A path-finding algorithm is used to identify obstacles in pathways to minimize shifting sequences for table forms, and to determine the position of the CLS. The simulation model proposed in this study can support rational decision-making for selection of optimal alternatives for table formwork operation in tall building construction.

2. Existing Operation Method for Table Formwork
A construction supervisor generally uses intuitive methods based on individual experience to determine factors affecting working time for table forms; operation of trolleys, the position of the CLS, and shifting sequences for table forms. There are two ways of using shifting trolleys: in the first, trolleys are used separately for installation or stripping work, while in the second, trolley use is integrated so each trolley can work on either floor. Supervisors may determine trolley movements through experimental operations on lower floors and calculate the number of required trolleys proportionally to the number of table forms\(^3\). The position of the CLS, which is generally situated at the center of an outer wall of the building is also determined by the supervisor intuitively to minimize the movement of all table forms. To determine the shift order of table forms, the general principle of stripping off inner table forms in preference to outer ones is usually observed to maintain the continuity of installation work. However, inner table forms unavoidably require a pathway to be moved to the outside; thus, the table forms installed in the pathway of the inner forms should be stripped and lifted first. The lifted table forms should be installed in lifted order, but table forms that block the pathway of subsequent table forms may be stacked temporarily for later installation.

These conventional heuristic methods do not take account of waiting times for moving trolleys caused by differences in times required for installation and stripping of table forms. Therefore, the idle times in shifting table forms cannot be predicted accurately. These methods can also require excessive use of equipment to reduce idle times and this could cause an increase in equipment rental cost instead. As well, the intuitive determination of CLS positions made to minimize the moving distance of trolleys is also limited because taller buildings frequently have irregular shapes. There are many alternative pathways to move table forms to the installation floor depending on the order of stripping off, and evaluating all such alternatives would be difficult for supervisors, frequently leaving the risk of taking longer pathways.

Such heuristic methods also have the fundamental problem of the variation in operational plans made by individual supervisors\(^9\).

Thus, previous studies have considered simulation for operations with table forms to analyze scientifically the productivity of equipment associated with table formwork to solve such problems. Kersting and Girmscheid (2010) created a model to simulate construction with table formwork and optimized the consumption of resources and cost for each project. In particular, the reality and accuracy of the simulation was improved by utilizing actual geometrical distances as moving distances for table forms instead of taking average values. However, the model was oriented to table formwork in construction employing tower cranes; thus, the activities and order of shifting table forms were not considered. Lim et al. (2013) created a simulation model of the use of table forms in construction employing a CLS by using CYCLONE and presented a construction schedule and cost according to the number of trolleys. However, the times required to shift all table forms were summarized by average values and the shifting of table forms was not taken into account. The operation of trolleys was limited to separated operation. Kim et al. (2014) established a simulation model for table formworks that employed a new independent lifting system and analyzed and compared the working time and cost with those incurred by using a tower crane. However, the number of trolleys and their mode of operation were also restricted and using the average value of shifting times of trolleys also limited the accuracy of the simulation. Thus, for accurate simulation of working with table formworks using CLS, a new simulation model taking into account the mode of operation of trolleys, position of the CLS, and the shift order of table forms is required.

3. Simulation-based Operation Planning Model for Table Formwork
The creation of an operation-planning model for table forms consists of four stages, as illustrated in Fig.1. In the first stage, information about the project is entered into the computer. The table form layout is configured on a grid system. Amounts of equipment and when they are required are entered in the simulation-based operation-planning model (SOM). The movement pathways of table forms are determined in the second stage. Through the algorithm determining the required shift order of table forms, the shifts and the position of the CLS are determined and the A* algorithm explores pathways to enable the computation of shifting distances of the respective table forms. In the third stage, the table formwork is simulated. The separated or integrated modes of operation of the trolleys are simulated and the trolleys are moved following the order determined at the second stage. In the fourth stage, an optimal operation plan for...
the table formwork is selected. The positions of the CLS and alternative shift orders for the table forms are created and the optimal shift order of table forms for each mode of operation is derived. The optimal alternative is selected from the derived operation plans while satisfying cycle time and cost input of formwork construction.

Fig.1. The Procedure of SOM

### 3.1 Input of Project Conditions
The project conditions are first entered into the SOM to explore shift pathways of table forms. For the exploration, the information of available and unavailable spaces and the sizes of shifted objects are required. The SOM converts the floor plan with the layout of table forms into a grid system to represent spaces and the sizes of shifted objects are used as coordinates. The interior of the building is made and the available space for shifting and internal structures are defined as obstacles. The stripped table forms are made shifting objects and the supports of the installed table forms are made obstacles.

### 3.2 Establishing Shifting Paths for Table Forms
#### 3.2.1 Path Finding Algorithm
The SOM explores the pathways to minimize shift distance by considering obstacles using the A* algorithm to find shift pathways for table forms. Workers would use the pathway of minimum distance to reduce labor\(^2\). The A* algorithm finds pathways of minimum distance by taking obstacles into account on each pathway. The A* algorithm finds pathways through nodes of the grid system. The nodes that minimize the distance from the start to the end are selected among surrounding nodes at the start and this process is repeated at every selected node to reach the final target node\(^3\). Because the algorithm does not compare selected pathways but proceeds by finding nodes along the path to the target, it requires less computation and thus is frequently used for efficient layout planning for traffic routes or in construction sites.

The restrictions on moving table forms depend on their shape and size. The SOM configures the table form as a rectangle with the length and width of the table form and the center of the rectangle defined as the shifting node. The breadth of the rectangle is recognized as the shiftable dimension on each pathway; if the pathway is narrower than the breadth of the rectangle, that pathway is marked as unavailable for shifting the table form.

#### 3.2.2 Algorithm to Determine Shifting Sequence
The SOM uses an algorithm to select the shift order of table forms. If the shift order is determined arbitrarily at each execution, then the numerous cases would cause unnecessary computation, and the resulting solution could even possibly be a local solution, or an unrealistic alternative. Therefore, the algorithm is based on actual formworks to exclude unnecessary computation and to establish a realistic model.

The algorithm for determining shift order firstly divides the space into two, based on an arbitrary placement of the CLS. In general, table forms are installed on one side of the CLS first, while the table forms on the other side are installed following the completion of the first side. The other side is utilized as the space to place table forms temporarily that would block the pathways of other table forms. Thus, the shift order algorithm distinguishes the spaces as an installation zone and a temporary placement zone according to the lifting points on the installation floor and also distinguishes the spaces as a stripping zone and temporary placement zone on the stripping floor after the completion of installation of table forms on one side.

The shift order algorithm creates the shift pathways by stripping the required number of table forms. The algorithm selects the initial table form arbitrarily and creates its shift pathway to the CLS. The shift pathway is created by connecting the central nodes of table forms to maintain the continuity of the installation work and the table forms of the selected nodes are stripped in preference to others. The selected table forms are sequenced in an order starting from the lifting point and the order of installation follows the order of stripping of table forms. Generally, the first table form stripped is the first one installed. If a stripped table form blocks pathways of subsequent table forms on the installation floor, then it is stacked up in a temporary space for later installation.

This study also proposes the use of a Block Index (BI) for table forms to reduce computation and the number of table forms placed temporarily. The BI describes the number of table forms that block the shift
of subsequent table forms in created shift pathways. The table form placed in front of CLS is excluded from the calculation of the BI because it must be stacked up temporarily. For example, three pathways to the CLS are shown in Fig.2., in which the eighth table form has been selected as the table form for initial installation. The pathway (a) would disable the installation of two table forms and thus the sixth and seventh table forms would be temporarily stacked up. In this case, the value of BI becomes two. The pathway (b) would disable the installation of five table forms; however, the installation would be enabled by temporarily stacking up the fifth table form. The value of BI for this case is one. Pathway (c) does not require any temporary stacking of table forms, so the value of BI is zero and this pathway is therefore selected as the preferred pathway.

In the next step, the shift order algorithm creates the order of stripping off table forms sequentially by iterating the process while arbitrarily selecting adjacent table forms. To maintain the continuity of installation work, adjacent table forms of the pathway selected in the previous step are selected arbitrarily for the next strip-off. The next table form to be stripped is selected among adjacent table forms and the preference is determined by computing BI values.

Finally, on completion of determining the shift order for all table forms, the shift distance of each table form is calculated using the A* algorithm. The times required for shifting loaded and unloaded trolleys are calculated considering the speeds of the trolleys. These were set to be 12 m/s for loaded ones and 25 m/s for empty ones.

3.3 Simulation of the Table Formwork Process
Table formwork employing a CLS can be simplified as illustrated in Fig.3., which shows the seven discrete activities that are repeated to complete the table formwork. First, table forms are stripped off and shifted to the CLS position for lifting. They are then loaded into CLS, lifted to the upper floor, and unloaded from the CLS. Then the unloaded table form is moved to the place of installation. The table formwork operation can be considered as separated or integrated, depending on the mode of operation of the trolleys.

3.3.1 Separated Operation of Shifting Trolleys

The simulation model of separated operation of shifting trolleys is as illustrated in Fig.4.(a). The trolleys on the stripping floor shift stripped table forms to the CLS and return to strip the next table form. The trolleys operating on the installation floor receive table forms unloaded from CLS and shift them to the point of installation. After installation, the trolley returns to receive the next table form. Each trolley operation is repeated until the table formwork is completed. The unloaded CLS is lowered immediately to the stripping floor to load subsequent table forms.

The events in the simulation model of separated mode of operation of trolleys require resources that are captured at the beginning of each event and released on the termination of the event. The stripping activity requires a stripping crew and stripping trolleys; the shifting activity on the stripping floor requires stripping trolleys; while the lifting activity requires the CLS. The unloading activity also requires the CLS and installing trolleys and the shifting activity on the installation floor requires installing trolleys. The installation of table forms requires installing crews and installing trolleys, while the temporary stacking of table forms only requires installing trolleys.

The simulation begins at the point where all trolleys are moving from lifting points for the stripping of table forms and the simulation terminates on completion of the installation of the final table form. Each trolley processes multiple table forms in sequence. The stripping trolley events will be terminated on completion of the last loading of stripped-off table forms to the CLS, while the installing trolley events will be terminated after the installation of the last table form. The CLS events are terminated after the unloading of the last table form. The simulation also calculates the simulated working time for table formworks.

3.3.2 Integrated Operation of Shifting Trolleys

The simulation model for the integrated mode of operation of shifting trolleys is as illustrated in Fig.4.(b). This mode of operation allows the nondedicated use of all trolleys for either installation or stripping of table forms; thus, a trolley carrying a stripped-off table form is lifted to the installing floor with the table form and used to install it. On completion of installation of a table form, the empty trolley is returned to the lower floor to strip more table forms.
During the creation of each alternative, the working table forms are derived using the shift order algorithm. The position of the CLS is selected arbitrarily from the places available. The alternative shift orders of the CLS and accompanying trolleys. The calculation difference resides in the activities of lifting or lowering the CLS is waiting at the stripping floor, then the call module determines the next move of the CLS, which can lift trolleys loaded with table forms from the stripping floor or it can lower empty ones from the installation floor. For example, if a trolley working on the installation floor returns to the lifting point while the CLS is waiting at the stripping floor, then the call module will order the CLS to lift to the installation floor. The techniques for installation and temporary stacking of table forms are identical with those in the separated mode of operation.

The events in the simulation model for the integrated mode of operation are identical with those in the simulation model for the separated mode of operation and thus the resources are also the same. The difference resides in the activities of lifting or lowering the CLS and accompanying trolleys. The calculation of simulated times is the same as that used in the separated mode of operation.

3.4 Selecting the Optimal Operation Plan for Table Formwork

The SOM optimizes alternatives for minimized working time by comparing the times required for each alternative. The position of the CLS and the shift order of table forms, which are the variables affecting shifting distances, are set as alternatives. The position of the CLS is selected arbitrarily from the places available. The alternative shift orders of table forms are derived using the shift order algorithm. During the creation of each alternative, the working times are derived in the simulation, compared with previously derived results, and the one with the fewest working hours is selected. This process is iterated until the alternative with minimum working hours is obtained. The alternatives are derived according to the mode of operation of the trolleys. For the separated mode of operation, alternative allocations of trolleys will also be tested. If the derived optimal alternative does not satisfy work duration and cost of formwork construction, the SOM is rerun after adjusting the hours per unit work and equipment requirements. After comparing the ultimate alternatives, the supervisor then selects the alternative that satisfies the constrained construction duration most economically.
4. Case Study

4.1 Case Description
To verify the applicability and effects of the simulation mode, the SOM was applied to a high-rise building construction using table formwork. The construction site was in Malaysia and is a composite building of 58 stories and height of 274 m. For the formwork processes, the typical floors were divided into two zones and the table formworks for the two zones were entered. As illustrated in Fig.5., 64 and 68 table forms were applied to zones A and B, respectively, and fillers were used for the remaining parts. A single CLS was assigned for the construction of each zone with one trolley on the stripping floor and one on the installation floor.

4.2 Application of SOM
The SOM was applied to zone A and simulated the operation with 64 table forms. The zone was mapped by dividing it into three areas to convert the map into the grid system and the supports of table forms and the members of frame structures were set as obstacles. Next, the order of shifting table forms was created using the relevant algorithm while the position of the CLS was selected among the 17 available. After the creation of alternatives for the SOM, simulations with the two modes of operation of the trolleys were performed to derive the optimal alternative. The times for installation and stripping of table forms, their loading and unloading, and lifting times were taken from a previous study and the values derived from the shift order algorithm were entered as the times for horizontal shifts.

4.3 Results and Discussion
Table 1. shows the results in working hours for each alternative obtained from the SOM for each mode of operation of table forms. The existing method required 10.31 hours of working time with the separated use of two trolleys, whereas the optimal operation in this mode of operation was 9.63 hours. The time required was 10.21 hours for the integrated mode of operation of trolleys. For the separated mode of operation of trolleys, about 6.62% of working hours were saved because of the difference in shift order in this mode of operation. For the integrated mode of operation, the shifting distance was minimized; however, the difference in mode of operation of trolleys was only 0.1%, meaning almost no savings in working hours compared with the existing approach. With two trolleys, a difference of about 5.86% in working hours was obtained for the same shift order because of the difference in modes of operation.

Both modes of operation of trolleys showed reduced working hours if additional trolleys were used. The integrated operation mode exhibited 23.21% reduction in working hours with three trolleys compared with the case with two trolleys; and the reduction in working hours increased to 40.25% with four trolleys. The separated operation mode showed a maximum 26.79% reduction in working hours with three trolleys and a maximum 41.95% with four trolleys. For both operation methods, the rate of reduction of time decreased as the number of trolleys increased.

The separated operation mode of trolleys required different working hours according to the assignment of trolleys to the installation and dismantling of table forms. In case S-3A, where one extra trolley was used on the installing floor, the working time decreased by 26.79% compared with 0.1% with one additional trolley on the stripping floor in case S-3B. Thus, the number of trolleys situated on the installing floor seemed to have more effect on the reduction of working hours. In cases S-4A, where one trolley was added to the installation floor, and S-4C, where one trolley was added to the stripping floor, there was no significant difference in reduction of working hours. However, in case S-4B, where two trolleys were used on each floor, working hours were reduced by 20.71% and 41.89% respectively. Thus, excessive input of trolleys to certain floors appeared to have insignificant effects.

Table 1. Comparison Work Times of Alternatives

| Operation | Case | Trolley input (EA) | Work time (h) | Reduction |
|-----------|------|-------------------|---------------|-----------|
| Traditional operation | 2 | I/F 1 | 10.31 | – |
| Integrated operation | I-2 | 1 | 10.21 | –0.99% |
| | I-3 | 3 | 7.84 | –23.98% |
| | I-4 | 4 | 6.10 | –40.85% |
| Separated operation | S-2 | I/F 1 | 9.63 | –6.62% |
| | S/F 1 | S-3A | I/F 2 | 7.05 | –31.64% |
| | S/F 1 | S-3B | I/F 3 | 9.62 | –6.72% |
| | S/F 2 | S-4A | I/F 2 | 7.07 | –31.44% |
| | S/F 2 | S-4B | I/F 1 | 5.59 | –45.79% |
| | S/F 3 | S-4C | I/F 1 | 9.62 | –6.72% |

Table 2. Operation Efficiency of each Operation Mode

| Equipment | Category | Integrated operation | Separated operation |
|-----------|----------|----------------------|---------------------|
| Trolley 1 Travel time (s) | 36002 | 34002 |
| Utilization rate (%) | 90.20 | 70.8 |
| Trolley 2 Travel time (s) | 36454 | 68 |
| Utilization rate (%) | 93.32 | 98.8 |
| CLS Travel time (s) | 10152 | 6966 |
| Utilization rate (%) | 13.98 | 10.22 |

Table 2. shows the operational efficiency of each method in the different modes. The two items of equipment were employed in identical shift orders. The shifting times of the two trolleys were found to be longer in the integrated operation mode than in
separated operation. Considering that the trolleys moved the same distance in both operation modes, the waiting times for table forms in the integrated operation were consequently longer than those with separated operation. With two trolleys in the integrated operation mode, the utilization rates of trolley 1 and trolley 2 were 90.20% and 93.32% respectively. Meanwhile, the utilization rate of the trolleys in separated operation mode were 70.8% for stripping and 98.8% for installation. Utilization rates were found to be relatively identically high in the integrated operation mode because the two trolleys were not distinguished, while utilization rates for the two trolleys showed a discrepancy in separated operation mode because of the inevitable waiting time of each trolley. For CLS-assisted operation, integrated operation mode showed a higher utilization rate and longer utilization hours compared with separated operation mode. Because of the additional waiting by trolleys after a call, utilization hours for the trolleys in the integrated mode were resultantly longer.

Fig.6. depicts the shifting order and location of the CLS under two circumstances: the conventional and SOM methods. The CLS was located at H for the traditional operation while for the system under SOM it was at I. The two results positioned the lifting system in similar locations, as building symmetry assisted the intuitive judgment of CLS location. Regarding the shifting order, the conventional method used sequential stripping of table forms starting from the building exterior, while SOM performed the same work starting from the inner part of the building. Table forms serving as obstructions on pathways were temporarily displaced on stacks for future installation in both cases. With the shifting order of the conventional method in Zone 'A-2', table forms 6, 7, and 8 were temporarily stacked to be installed after table form 33. However, SOM always selected cases with fewer temporary stacks even with a roundabout route, and thus did not produce any temporary stacks.

Table 3. shows comparative results for working times and travel distance of the two operation methods. The travel distance for the shifting order derived by SOM was 5636.83 m, a reduction of 4.47% from that obtained with the conventional method. Working time provided by SOM was reduced from that provided by the conventional method by 6.62%, ultimately yielding a result of 9.63 hours. The higher disparity in working hours than that for travel distances for identical operation modes was mainly because of temporary stacks of table forms. A total of 11 table forms were temporarily stacked with the conventional
operation method, which is more than double the number of stacked table forms with the proposed SOM. Temporary stacks result in not only extensions of travel distance, but also lengthening of working time because of the additional activities associated with temporary displacements of table forms.

The results obtained from the case study demonstrate the higher effectiveness of SOM as a more suitable and appropriate method for handling table forms in construction sites than the traditional operation method. Compared with the conventional method, which is dependent upon heuristic approaches, SOM provides more feasible alternatives for operating and managing table formwork construction, including the resulting working hours and resource allocation. The simulation model also enables productivity analysis on equipment operation and calculation of appropriate equipment combinations under predetermined constraints.

5. Conclusions

This study proposed a simulation-based operation-planning model for table formwork for its efficient use in tall building construction. The proposed model searches for an optimal shifting order of table forms using a path-finding algorithm, and calculates working hours by conducting a case study to provide alternatives for the operation method and resource allocation. In the case study, the authors derived an operation method and shifting order that reduced operation hours for table forms with identical resource inputs over those for the conventionally applied heuristic method. Furthermore, the proposed system allowed comparative analysis of optimal decision alternatives suitable for a specific construction project by determining operation efficiency and working hours according to additional resource input and operation methods. The model developed in this study will be utilized for decision making by construction supervisors for selection of optimal horizontal formwork operation plans suitable for tall building construction with constrained resources.

Acknowledgement

This research was supported by a grant (16AUDP-B106327-02) from the Architecture & Urban Development Research Program funded by the Ministry of Land, Infrastructure and Transport of the Korean Government.

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