Automated Lifting System Integrated with Construction Hoists for Table Formwork in Tall Buildings

Taehoon Kim\(^1\); Hyunsu Lim\(^2\); Hunhee Cho\(^3\); and Kyung-In Kang\(^4\)

**Abstract:** In tall-building construction, the equipment-driven table formwork method is a useful alternative for improving productivity of horizontal formwork with less skilled labor. The lifting system significantly affects the productivity and costs of table formwork operation. This study proposes a new system integrated with the construction hoists for automating the lifting process of table formwork. The system targets crane-independent transportation for productivity improvements while overcoming the limitations of the existing independent lifting system, which include high initial cost and extra work for assembly and operation. In a case study, the proposed system showed 49.4% improved productivity over a tower crane, and equipment costs were 73.8% lower than those of the existing independent system. The simplified structure of the system through integration with the hoist could minimize the additional time and cost inputs for its assembly and operation. The proposed system could provide more flexible and stable scheduling at a lower cost in tall-building construction with short cycle times and excessive lifting loads. DOI: 10.1061/(ASCE)CO.1943-7862.00000884. © 2014 American Society of Civil Engineers.

**Author keywords:** Automated lifting system; Construction hoist; Table formwork method; Tall-building construction; Construction Materials and Methods.

**Introduction**

**Background**

In tall-building construction with reinforced concrete structures, enormous efforts for enhancing formwork efficiency are invested in ensuring successful project completion. Formwork operations represent approximately 25% of the total construction duration (Ling and Leo 2000) and directly affect subsequent construction activities, such as electrical, mechanical, and finishing work (Proverbs et al. 1999). To secure the business value of the project, activities, such as electrical, mechanical, and finishing work (Proverbs et al. 1999) and directly affect subsequent construction processes largely determine the idle time between activities. The tower crane (T/C) method is used generally for vertical transportation of table forms with other materials. However, this lifting method causes productivity losses by frequent idle times occurring at the stripping floor because the T/C has to support table forms while addressing the problems with the lifting operation of the T/C.

To address these problems, several construction sites have recently used independent lifting systems. To lift the table forms, the system raises the lifting platform itself through independent lifting masts (DOKA GmbH, Amstetten, Austria) or uses a winch attached above the platform (PERI GmbH, Weissenhorn, Germany), which enables the crane-independent transportation of table forms. However, the initial setup of these systems requires much time, and the initial cost increases significantly because of their complicated configurations and heavy weight. Moreover, subsidiary work for raising and fixing the system itself might be repeatedly required, depending on the progress of construction work.

**Research Objectives and Methods**

The objective of this paper is to introduce an automated lifting system integrated with construction hoists for more-efficient table formwork operations in tall-building construction. The system proposed in this study combines the lifting platform with the masts of the existing construction hoists to move the platform automatically without installing the independent devices. This system minimizes the cost increases and the extra work for its assembly and operation while addressing the problems with the lifting operation of the T/C. The system will be useful for tall-building projects, which require rapid cycle times with excessive lifting loads.
This study introduces a new system for automating the lifting process of table formwork and examines the feasibility of the proposed system. In the first step, the table formwork methods in tall buildings are reviewed to determine targets for improving the system. Next, the existing table formwork lifting methods—the T/C and a crane-independent lifting system (CLS) with similar operating processes to the system proposed in this study—are investigated.

In the second step, on the basis of previous reviews, an automated lifting system combined with a construction hoist (ALICON) is proposed. The configurations and operation method of the ALICON are introduced, and its structural safety is also checked against designed elements according to specified safety certificate criteria for construction hoists (Ministry of Employment and Labor 2012), such as type and calculation of loads, load factors, and allowable stress. Finally, a mock-up test is performed to verify the system’s technical performance and to identify any problems during operation.

In the third step, the feasibility of the ALICON is verified by applying it to an actual tall-building project and comparing the performance of the lifting method using the ALICON with existing systems—the T/C and the CLS—in terms of productivity, lifting loads, and equipment cost. First, a computer simulation technique called Cyclic Operation Network (CYCLONE) (Halpin and Riggs 1992) is used, which is one of the most widely used simulation methods for construction projects (Hong and Hastak 2007; Luo and Najafi 2007), to compare the productivity of the table formwork operation with each system. Next, lifting loads of the T/C during a floor cycle are compared on the basis of a 3-day cycle. Lastly, the rental cost of the ALICON is estimated by considering its production and maintenance costs, life expectancy, and expected rate of return and is compared with those of existing systems.

**Table Formwork and Lifting Methods in Tall Buildings**

**Table Formwork Method in Tall Buildings**

When considering recent construction environments, the table formwork method has become an attractive alternative for efficient horizontal formwork. Structural systems for typical floors have been increasingly simplified in tall-building projects to improve constructability. In Korea, for tall buildings with 3- or 4-day cycle times per floor and more than 40 stories, flat or flat-plate slabs have been applied as the structural system in 55 of 58 sites (Kim 2013). The building construction industry has also suffered from a lack of skilled labor and from steep wage increases. Therefore, the equipment-driven table formwork method can be more profitable in terms of productivity, costs, and quality than other methods using handset forms.

Table forms can be classified into two types—flying and modular. Flying table forms have limited application in diverse building shapes, although they enable high productivity in square building structures. The modular table forms, which are generally 2.0–2.5 m wide by 4.0–5.0 m long, can be applied more easily in the construction of tall buildings of diverse shapes.

In modular table formwork operations, the type, performance, and inputs of the equipment significantly affect productivity and cost. The modular table formwork requires equipment for horizontal and vertical transportation of form units. In particular, the equipment for vertical lifting has a much higher initial cost than that for horizontal shifting. In addition, the equipment’s type and performance for vertical lifting largely affects the sequence of table formwork operation and the lag time between activities. Therefore, this study focused on a new lifting system for efficient modular table formwork operation.

**Existing Lifting Methods for Table Formwork**

**Tower Crane**

The T/C is the universal equipment for vertical transportation of table forms with other materials. Tower cranes transport table forms from the stripping floor to the position where they are to be installed. In the lifting process, two types of equipment—the transport fork and the lifting platform—are used to connect the form unit with the T/C. As shown in Fig. 1, the lifting platform is preferred for enhancing work safety and avoiding interference between the T/C and ACS because the ACS has been used in the construction of

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**Fig. 1.** Table formwork using T/C and lifting platform (Kumho E&C 2009, reprinted with permission from Kumho E&C)
most tall buildings in Korea (Kim 2013). Fig. 1 shows the process for the table formwork using the T/C and lifting platform.

Although this method has been generally applied in table formwork because of its economic benefits in terms of equipment cost by using T/C and simple structured platforms, it has limitations. Because the T/C holds a form unit until its installation is complete, productivity losses are incurred by the frequent idle times at the stripping floor until the next unit is connected with the T/C. The weather and the skill level of the operator also significantly affect productivity. In addition, investigation of five construction sites showed that the T/C was used for table form erection for approximately half a day to a day. Thus, such substantial lifting loads in the T/C can lead to delays in the schedule, especially in tall-building construction, which requires short cycle times and large amounts of materials to be transported.

Crane-Independent Lifting System

Crane-independent lifting systems are used to cope with the problems associated with lifting by using T/Cs. The CLS targeted in this study transports the table forms vertically by raising the lifting platform itself through independent masts and supporting units, as shown in Fig. 2. The lifting platform is 2.70 m wide by 4.93 m long, with a lifting speed of 10 m/min and a maximum payload of 16.5 kN during lifting. The table forms moved to the installing floor by the platform are transported horizontally to targeted installation positions by the shifting trolleys, which indicates that the table units can be transported regardless of the installation work.

Although this lifting method can overcome the problems associated with the T/C, it still has some limitations. The initial equipment cost is considerably higher than that of the T/C method because of the high rental cost of the CLS by additional components, such as masts and supporting units. It also requires a long time, approximately 2 days, for the initial assembly of the system, including anchor burial and fixing the supporting units and profiles, masts, and the lifting platform. This lifting method also requires additional repetitive actions during CLS operation, such as anchoring and tying the masts to the structure for approximately half a day at every floor.

Automated Lifting System Integrated with Construction Hoists

System Concept and Configurations

The system proposed in this study targets crane-independent transportation of modular table forms while overcoming the limitations of the existing independent lifting system, i.e., high initial cost, time-consuming initial setup, and additional work for lifting the system itself. To achieve these objectives, this study proposes the integration of the automated lifting system with a construction hoist. For tall-building projects, two to four hoists on a building are generally installed using masts fixed on the ground. The masts are set up repeatedly according to construction progress to extend the operating distance of the hoist. The concept of the proposed system is to combine the lifting platform with the mast of the existing construction hoist installed on the external face of the building. The existing hoist is generally operated up to the floor below the ACS, which is attached at the upper floors, as shown in Fig. 3(a). Thus, the proposed system could be applied without disrupting the existing hoist’s operation because the system is operated at the floors where the ACS was attached [Fig. 3(b)]. This will also allow a significant reduction in the work required for its assembly and operation and in the complexity of the configuration.

The system consists of three parts: a lifting platform, an operating unit, and a control unit (Fig. 4). The lifting platform for loading table forms comprises form supports, a deck floor and guardrail, and a loading gate. The form supports for the table forms moved by trolleys were designed to be 2.2 m wide and 2.5 m high, by considering the general size of a form unit and a shifting trolley. The operation can be simplified as the activity of fixing the unit to the lifting platform is removed by using the sliding deck attached on the form supports (Fig. 5). The deck floor was designed to be a maximum of 3.5 m wide and 5.0 m long, although it can be adjusted to suit the specific site conditions such as the size of forms and construction hoists. The deck floor has more-rigid structural frames inside the form supports where the shifting trolley is loaded. In addition, the basket for loading the system’s power cable is installed below the deck floor. Guardrails enclose the deck floor to prevent workers from accidentally falling. The loading gate has a doorstop and limit switch to prevent abnormal operation of the lifting platform; that is, the lifting platform will not work if the gate is open.

The operating and control units have components similar to the existing construction hoists. The operating unit includes an electric motor and gears and guide rollers for combining with the lifting masts of the hoist. The motor capacity was determined to be 5.5 kW according to the motor capacity calculation introduced by Ryff (1988). The lifting speed of the platform was set at 10 m/min by considering the performance of the existing system and safety requirements.

The control unit prevents abnormal working of the system and controls the movement of the system. It includes double devices—upper and lower limit switches and a power-cut switch—to prevent the system from exceeding the transporting distance limit, a governor for compulsory stopping in case of an accidental fall of the system, and a load cell. These elements are connected to the control panel. The system also includes a device for unmanned operation and control of the system that is connected to beepers inside the building. It includes limit switches for double-checking the conditions of the loading gate, for detecting workers or objects when the system is moving, and for preventing an error by repetitive sensing of the transporting distance and a sensor for measuring the transporting distance.
System Assembly and Lifting Method

The initial assembly of the proposed system is considerably simpler than the CLS. Although the operation mechanism of the system is similar to the CLS, difficult or time-consuming tasks such as anchoring and fixing supporting units and masts are not required because the system uses the mast of the construction hoist that is already installed. The assembly of the proposed system can be easily performed by fixing the deck floor—including operation and control units—to the mast of the construction hoist after erecting guardrails and the loading gate on the deck floor. Thus, the proposed system can be initially assembled in a short time, approximately half a day, compared with the CLS, which takes approximately 2 days to assemble.

Just like the CLS, the system is raised as the construction work progresses. The proposed system is raised by extending the lifting masts of the construction hoist. The masts are extended by using an erection crane installed on the upper cage of the hoist, and then wall ties are installed to fix the masts to the building structure (Fig. 6). Rather than having general wall ties installed at two-floor intervals, the wall ties for this system are installed at every floor because the system moves up to the top floor, which leads to a cost increase for wall ties and additional work. To address this problem, a newly designed wall tie is introduced in this study. The portable wall tie could be untied by disconnecting the tie bar and raised along the mast through rollers attached to the side post of the mast [Fig. 7(a)]. The tie bars were then reconnected, and the wall tie was anchored to the floor [Fig. 7(b)]. That is, this wall tie was used only for fixing the masts to the top floor, and other wall ties were installed at two-floor intervals. These were done to raise the existing construction hoists; thus, additional work for lifting the system itself were not required.

Structural Safety of the System

The structural safety of the system was examined on the basis of the following assumptions: (1) the system is attached to the mast of a hoist with high-transporting speed, and the masts are installed up to 400 m high (266 masts overall) to suit tall-building construction. (2) The loads applied to all elements of the system including vertical and horizontal, and earthquake and wind loads at the uppermost section of the construction hoist were estimated. (3) Allowable wind loads were set as 16 m/s under normal conditions and 50 m/s during storms. Wind loads applied to wall ties were not considered because their effect on the entire structure of the wall tie is insignificant. The wind direction was set to be the same as the building direction to allow for unfavorable conditions.

First, the loads applied to the elements of the system were estimated. The total vertical ($W_v$) and horizontal ($W_h$) loads were...
calculated to be 41.25 and 6.60 kN, respectively, by the sum of the self-weight of the system (17 kN) and the maximum loading capacity (16 kN) multiplied by load factors, 1.25 and 0.2, respectively. The earthquake loads ($W_e$) were calculated to be 2.55 kN, considering the self-weight and load factor, 0.12. The wind loads applied to the masts and the system under normal conditions ($W_{wn}$) and during storms ($W_{ws}$) were calculated separately by using Eqs. (1) and (2), respectively. The wind force resistance areas were 0.71 and 5.5 m$^2$ for the mast and the system, respectively, and the wind force coefficient was 1.6

$$W_{wn} = 83.3 \times \sqrt{h} \times C \times A$$

$$W_{ws} = 816.3 \times \sqrt{h} \times C \times A$$

where $h$ = height from ground level; $C$ = wind force coefficient; and $A$ = wind force resistance area.

Next, the stress applied to each element was estimated on the basis of the worst load conditions. For the lifting platform, the stress and displacement for each component were estimated by using a commercial structural analysis program, MIDAS Gen 2013 version 1.1. This component required a more accurate examination because of its complicated structure. Finally, the stress applied to each element was checked to determine whether it exceeded allowable values.

Table 1 shows the results of the structural safety check for each element. For the lifting platform, the stress did not exceed the allowable value for any component [Fig. 8(a)]. The displacement probably would not affect safety and usability, although it was 12 mm at the maximum because this part was not in the area of direct application of the loads [Fig. 8(b)]. For the brake, the result ensured structural safety as the allowable value for the brake took into account the ratio of the braking torque to operating output torque. These results showed that all elements of the proposed system had sufficient capacity to ensure structural safety.

Fig. 5. Operation process of the proposed system: (a) shift to the loading gate; (b) load onto the lifting platform; (c) lift up the platform; (d) unload from the platform

Fig. 6. Lifting process of the proposed system: (a) untie and lift up the wall tie; (b) lift the mast; (c) fix the mast; (d) tie the wall tie
Mock-Up Test

A mock-up test was performed to identify whether the system met the mechanical performance specifications and whether there were any problems during operation. Thirty experiments were performed, lifting a table form unit up and down 10 m (Fig. 9). The average time for lifting up and down was 1.12 and 1.09 min, with a standard deviation of 0.068 and 0.079, respectively. This result showed that the rated speed of the system was satisfactory. In addition, there were several tests for the braking performance in case of an accidental fall of the system. Immediate braking by the governor was achieved without any problems. In the test, there was one trivial problem: the loading gate sagged slightly during opening because of tolerance by the pinned connections between supporting posts of the gate and deck floor. To address this problem, the connection type was replaced with a rigid connection.

Case Study

Case Description

To verify its applicability and to demonstrate its benefits, the proposed system was applied to a tall-building project that applied a modular table formwork method. The table formwork method in this project was applied on typical floors of two residential buildings with 40 and 50 stories.

The case study was carried out on typical floors in the 50-story building. In the case study building, typical floors were divided into two zones and floor cycles, which indicates that the number of working days for a typical floor was 3 or 4 days. The average height of a typical floor was 3.3 m. For table formwork operation, three sets of table forms (56 table units per floor) were inputted, as shown in Fig. 10. One shifting trolley and one T-type T/C with two loading platforms were inputted for horizontal and vertical shifting of table forms.

System Application

First, the productivity of table formwork operations by each of the three lifting systems, T/C, CLS, and ALICON, was analyzed. This study developed a CYCLONE model for table formwork using the proposed system (Fig. 11). The details of the model are as follows: (1) Node 2 refers to stripping work by a stripping crew and a shifting trolley. (2) Nodes 5–9 refer to the shifting phase on a stripping floor. Once a crew loads a table unit onto the trolley, the trolley moves to the lifting platform. The transported unit is unloaded when the platform becomes available, after which the trolley moves back to the position for stripping work of the next unit. (3) Nodes 7–14 describe the lifting phase from the stripping to the installing floor. The unit is unloaded when a trolley on the installing floor becomes available, and then the platform moves down. (4) Nodes 12–19 show the shifting and installation phase on the installing floor. Once the table unit is loaded, the trolley moves to the targeted installation position, and then it moves back to the platform after an installation crew completes the installation work. Table 2 shows the duration input data for simulation. On the basis of field investigations of a construction site using the table formwork method (Lim et al. 2013), a triangular distribution was used, which is not greatly affected by the number of data and makes possible simple calculation (Back et al. 2000; Hong and Hastak 2007) of the duration of stripping and installing a form unit. The travel time of a shifting trolley was inputted as a uniform distribution according to the traveling distance and the average velocity of a trolley of 12 m/min, as detailed in Kersting and Girmscheid (2010) from Eq. (3). On the basis of the results of mock-up tests and field investigations, the durations of Nodes 7, 10, 12, and 14 were defined as deterministic values because they showed little variation

\[
T_i = \frac{\Delta x_i + \Delta y_i}{V_i}
\]

where \(T_i\) = travel time of a shifting trolley for table unit \(i\); \(V_i\) = average velocity of a trolley; and \(\Delta x_i\) and \(\Delta y_i\) = \(x\)-and \(y\)-axis distance between the center of the lifting platform and the table unit \(i\), respectively.

The CYCLONE models for table formwork using the T/C and the CLS were introduced from Kwon et al. (2013). In the model for table formwork using T/C, the lifting time was inputted as a
uniform distribution, ranging from 0.27 to 0.52 min, based on the hook travel time equations from Zhang et al. (1999) and general values for transporting velocity from Kim et al. (2009). The durations of lifting the CLS and fixing and unfixing the form unit were assumed as 1 min each. In the models using the CLS and the ALICON, it was assumed that there were two trolleys on the floor of the table form installation, considering that the installation time was longer than the stripping time.

In the second stage, the lifting loads of the T/C when using the T/C and the ALICON during a floor cycle were compared. The lifting loads using the CLS were excluded from the comparison because they were almost the same as those obtained using the ALICON. Table 3 presents the lifting loads and transportation time in Zone A based on the construction report of the case site (Kumho E&C 2009). The lifting loads in Zone B were the same as in Zone A except for the table forms (30 units). In the case study building, the lifting time for the table forms was set according to previous simulation results. In this study, the analysis was performed on the basis of a 3-day cycle, which requires more lifting loads per day than a 4-day cycle. During a floor cycle, the construction on the first day of Zone A and on the third day of Zone B progressed simultaneously.

Finally, the equipment cost of the proposed system was compared with that of the T/C and the CLS. In this study, the rental cost of the proposed system was estimated as follows (Lee 2006): (1) the expected production cost ($C_e$) was estimated on the basis of the production cost of the prototype by using the program evaluation and review technique (PERT), as shown in Eq. (4). (2) Life expectancy ($n$), maintenance cost ($C_m$), and expected rate of return ($i$) were set through an expert's interview with a representative from the hoist manufacturer because the proposed system had mechanical characteristics similar to the construction hoists. (3) The total expected investment ($TC_e$) was calculated from Eq. (5). (4) The rental cost per year ($RC_e$) of the proposed system
was estimated from Eq. (6) by considering a payback period of 5 years. The rental costs of the lifting platform were deduced when using the T/C and the CLS through a survey from the form manufacturers. The rental cost of the T/C was excluded from the comparison because the T/C was used regardless of the lifting methods.

\[
C_e = \frac{O + 4M + P}{6}
\]  

(4)

where \( O \) = optimistic cost; \( M \) = most likely cost; and \( P \) = pessimistic cost.

\[
TC_e = C_e + C_m \times \left\{ \frac{[(1 + i)^n - 1]}{i \times (1 + i)^n} \right\}
\]  

(5)

\[
RC_e = TC_e \times \left\{ \frac{i \times (1 + i)^5}{[(1 + i)^5 - 1]} \right\}
\]  

(6)

**Results and Discussion**

Table 4 summarizes the results of the simulated productivity and cycle time from each CYCLONE model. Using the ALICON enhanced the table formwork productivity by 49.4% compared with the T/C. Based on the average cycle time required for the erection of a table form unit (5.9 min), total erection time for 30 units using the ALICON was 2.9 h, which was 1.5 h faster than when using the T/C. The table formwork using the ALICON also showed slightly improved productivity compared with using the CLS, as the activities of fixing and unfixing the table forms were excluded. The results indicated that the proposed system not only could enhance the productivity of table formwork operation remarkably compared with the T/C by minimizing the idle time during erection but also would perform competitively in terms of the formwork productivity compared with the CLS.

Table 5 compares the overall lifting loads of the T/C (when used) with those of the ALICON as the lifting system for the table forms. As shown in the simulation results, the transportation time of table forms by the T/C was set to 4.4 h for Zone A and 3.8 h for Zone B because the T/C was used continuously during table formwork erection. Meeting the planned floor cycle only by using the T/C would have required early work every day and night work on the first and second days to lift the reinforced bars. A lifting time of more than 12 h for the T/C occurred only for the concrete frame constructions on the first and second days. Frequent overwork can lead to a decrease in labor productivity, and the schedule could also be delayed if additional lifting loads occurred. In contrast, when applying the ALICON, the early work for lifting the reinforced bars becomes unnecessary because the ALICON can transport the table forms and their shores besides saving 1.5 h on erecting the table formwork. As a result, the lifting loads on the T/C were reduced to 8.1 h on the first and second days, and the total service time was reduced to 12 h. The results showed that the proposed system could provide a more stable scheduling by greatly reducing the lifting loads of the T/C.

Table 6 presents the estimated equipment cost for the case study building. Based on the production cost of the prototype, and in consultation with professionals who had participated in manufacturing the prototype, the estimates for the optimistic, pessimistic, and most likely production costs were $38,000, $50,000, and $42,000, respectively. In addition, the life expectancy was set to 10 years, with a maintenance cost rate per year of 15% of the expected production cost and an expected rate of return of 13% per year. Based on Eqs. (4)-(6), the rental cost per year was $22,004, making the cost per month $1,834. Table 6 shows the rental costs of the lifting platform to be $1,000 and $7,000 per month for the T/C and the CLS, respectively. Thus, the proposed system could save 73.8% of the rental cost ($5,166 per month) compared with the CLS. For the case study building, the total equipment costs was $30,000 when using the T/C (considering rental duration of 12 months for two lifting platforms and one trolley at $500 per month). In contrast,
the CLS and ALICON would cost $186,000 and $62,016, respectively, when considering two additional trolleys. As a result, for the case study, the ALICON could save approximately $124,000 in total equipment costs over CLS, but compared with the T/C, equipment cost would increase by approximately $32,000. However, the use of the T/C incurs labor cost increases and productivity losses by early work and overwork. For the case project, the additional labor cost was estimated to be approximately $24,400 for 19 floors ($1,284 per floor) when performed on a 3-day cycle, based on the analysis results of lifting loads and labor cost criteria in Korea. In addition, considering schedule delays from excessive lifting loads and weather conditions, the application of the ALICON may be more useful for fast and stable scheduling with low cost.

Table 2. Duration Input Data for Simulation

<table>
<thead>
<tr>
<th>Node</th>
<th>Activities</th>
<th>Value type</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
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<tbody>
<tr>
<td>2</td>
<td>Strip table form</td>
<td>Triangular</td>
<td>1.00</td>
<td>2.24</td>
<td>3.83</td>
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<tr>
<td>5, 15</td>
<td>Shift table form</td>
<td>Uniform</td>
<td>0.44</td>
<td>—</td>
<td>2.00</td>
</tr>
<tr>
<td>7</td>
<td>Load table form</td>
<td>Deterministic</td>
<td>—</td>
<td>1.00</td>
<td>—</td>
</tr>
<tr>
<td>9, 19</td>
<td>Return trolley</td>
<td>Uniform</td>
<td>0.44</td>
<td>—</td>
<td>2.00</td>
</tr>
<tr>
<td>10</td>
<td>Lift up the system</td>
<td>Deterministic</td>
<td>—</td>
<td>1.11</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>Unload table form</td>
<td>Deterministic</td>
<td>—</td>
<td>1.00</td>
<td>—</td>
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<tr>
<td>14</td>
<td>Lift down the system</td>
<td>Deterministic</td>
<td>—</td>
<td>1.08</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>Install table form</td>
<td>Triangular</td>
<td>3.65</td>
<td>4.88</td>
<td>6.33</td>
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Table 3. Lifting Loads of T/C on Zone A of Case Building (Kumho E&C 2009, Reprinted with Permission from Kumho E&C)

<table>
<thead>
<tr>
<th>Day</th>
<th>Materials</th>
<th>Lifting time per cycle (min)</th>
<th>Total lifting amount</th>
<th>Number of lifts</th>
<th>Total lifting time (h)</th>
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<tbody>
<tr>
<td>1st</td>
<td>Rebar for core walls</td>
<td>15</td>
<td>26 t</td>
<td>15</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Prefabricated rebar</td>
<td>15</td>
<td>5 units</td>
<td>5</td>
<td>1.3</td>
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<tr>
<td></td>
<td>for columns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forms for stairs</td>
<td>30</td>
<td>2 units</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Table form shores</td>
<td>10</td>
<td>500 units</td>
<td>10</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Table forms</td>
<td>—</td>
<td>26 units</td>
<td>—</td>
<td>Simulation</td>
</tr>
<tr>
<td>2nd</td>
<td>Rebar for slabs</td>
<td>15</td>
<td>14 t</td>
<td>8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 4. Comparison of Simulated Productivity of T/C, CLS, and ALICON Models

<table>
<thead>
<tr>
<th>Category</th>
<th>T/C</th>
<th>CLS</th>
<th>ALICON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total simulation time (min)</td>
<td>8,751.5</td>
<td>6,378.7</td>
<td>5,859.8</td>
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<tr>
<td>Cycle number</td>
<td>1,000.0</td>
<td>1,000.0</td>
<td>1,000.0</td>
</tr>
<tr>
<td>Average cycle time (min)</td>
<td>8.8</td>
<td>6.4</td>
<td>5.9</td>
</tr>
<tr>
<td>Productivity per time unit (cycle/h)</td>
<td>6.9</td>
<td>9.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Total erection time (h)</td>
<td>4.4</td>
<td>3.2</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 5. Comparison of Overall Lifting Loads of T/C by Using T/C and ALICON

<table>
<thead>
<tr>
<th>Lifting systems</th>
<th>Day</th>
<th>Service time (h) (a)</th>
<th>Lifting time (h) (b)</th>
<th>Operation rate (%) (b/a × 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/C</td>
<td>1st</td>
<td>14</td>
<td>12.6</td>
<td>90.0</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>14</td>
<td>13.2</td>
<td>94.3</td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>12</td>
<td>2.0</td>
<td>16.6</td>
</tr>
<tr>
<td>ALICON</td>
<td>1st</td>
<td>12</td>
<td>8.1</td>
<td>67.5</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>12</td>
<td>8.1</td>
<td>67.5</td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>10</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
**Table 6. Equipment Cost for T/C, CLS, and ALICON Systems**

<table>
<thead>
<tr>
<th>Lifting systems</th>
<th>Rental cost (U.S. dollars/month)</th>
<th>Total equipment cost (U.S. dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/C</td>
<td>1,000*</td>
<td>30,000</td>
</tr>
<tr>
<td>CLS</td>
<td>7,000</td>
<td>186,000</td>
</tr>
<tr>
<td>ALICON</td>
<td>1,834</td>
<td>62,016</td>
</tr>
</tbody>
</table>

*Rental cost of a lifting platform in the lifting method using the T/C.

These results reveal that the proposed system can overcome the limitations of both the T/C and the independent lifting system and is potentially useful for table formwork operation in tall-building construction. The proposed system can minimize productivity losses from frequent lag times between activities, which is a significant limitation of the lifting method using the T/C. Moreover, when applying the proposed system, the productivity of table formwork could be easily varied by changing the number of inputs of shifting trolleys, which have a relatively small equipment cost. For the case study, the table formwork productivity when using the proposed system could be improved by approximately 16.9% by including one additional trolley on the stripping floor, whereas including additional trolleys had little effect on productivity when using the T/C. This indicates that the system makes it easier to deal with schedule changes caused by unexpected delays. Through alleviating lifting loads of the T/C, the system not only allows a more stable concrete framework but also minimizes increases in the labor cost caused by early work or overwork for material transportation. Lastly, the proposed system has remarkably reduced initial equipment costs compared with the CLS, and its simple assembly and operation process could also help reduce additional time and labor inputs.

Despite these advantages, several aspects should be considered for practical use. Given that twin hoists are generally attached in tall-building construction, the system should be installed in the upper part of one of the two hoists. Therefore, an additional compulsory device to prevent accidental clashing with the hoist would contribute to enhancing safety, although the limit switches for controlling the transportation distance and the governor for compulsory stopping of the system are readily attached. In addition, as the system is integrated with the construction hoist, the optimum positioning for installation and the size of the hoist will have to be decided in discussions between form and hoist suppliers in the construction planning stage.

**Conclusions**

This study proposed an automated lifting system integrated with construction hoists for efficient table formwork operation in tall-building construction. In terms of the productivity for table formwork, this system provided improved results by reducing the lag time and required tasks compared with both the tower crane and the independent lifting system. Furthermore, its simple structure and integration with the construction hoist could remarkably reduce the equipment costs compared with the existing independent lifting system. The proposed system will help practitioners to ensure more flexible and more stable scheduling at reduced cost in tall-building construction. In the future, actual application in tall-building projects will be necessary for further improvement of the performance and operation of the proposed system.

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**References**


