# Simulation-Based Schedule Estimation Model for ACS-Based Core Wall Construction of High-Rise Building

Taehoon Hong, A.M.ASCE[1]; Kyuman Cho[2]; Changtaek Hyun, M.ASCE[3]; and Seungwoo Han[4]

**Abstract:** Many existing studies about construction schedule management focus on the planning phase of a project, particularly on schedule estimation based on the labor resources involved in the project. However, equipment resources, which are another crucial factor in the productivity of a construction project, have not been considered in existing research. Therefore, this study aimed to develop a schedule estimation model considering both labor and equipment resources. For the purpose of this study, core wall construction was selected because it is a very important construction activity in terms of schedule estimation for high-rise building construction. To develop a schedule estimation model for core wall construction, an in-depth case study was conducted. On the basis of the results of the case study, a simulation model was developed using the CYCLONE method. Finally, by using the results of the simulation, a schedule estimation model for core wall construction was developed by conducting multiple-regression analysis. By using the developed model, a project manager can easily, quickly, and accurately perform schedule estimation when there are problems that may cause construction schedule delays during the construction phase. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000300. *© 2011 American Society of Civil Engineers.*

**CE Database subject headings:** Scheduling; Core walls; High-rise buildings; Simulation.

**Author keywords:** Scheduling; Core walls; High-rise building; Simulation.



## Introduction

During the construction phase, a construction project often faces problems that were not anticipated in the planning phase (i.e., weather, soil conditions, a labor strike, or the owner's financial instability). Because such unexpected circumstances can have a huge impact on the construction schedule, a schedule estimation method is needed that allows construction project managers to prepare for such unexpected occurrences in the construction phase (Nasir et al. 2003; Okmen and Oztas 2008).

Many previous studies on construction schedule estimation have aimed at predicting and adjusting the duration of the construction in the project-planning phase. For scheduling estimation, these existing studies consider two key issues: (1) the labor resource-driven scheduling method, and (2) optimization scheduling and resource utilization. Regarding the labor resource-driven scheduling method, researchers have conducted various studies to improve laborers' idleness and increase their productivity. As a result, researchers have proposed various methodologies that can help improve labor availability and work continuity (Ashley 1980; Birrell 1980; El-Rayes and Moselhi 1998; El-Rayes 2001; Reda 1990; Vanhoucke 2006). With regard to the optimization of scheduling and resource utilization, existing studies have developed various algorithms and methodologies to optimize the project duration according to the resource to be used (Eldin and Senouci 1994; Hyari and El-Rayes 2006; Kavanagh 1985; Moselhi and El-Rayes 1993; Reda 1990; Russell and Caselton 1988; Selinger 1980). This literature review shows that existing scheduling studies aim at (1) maximizing the productivity of laborers or crew by effective utilization of these resources, and (2) optimizing the utilized resources and the corresponding duration by implementing various methodologies and algorithms.

Project managers or engineers can see the resources (i.e., labor, equipment, and materials) inputted into the project more accurately in the construction phase than in the project-planning phase. Schedule estimation in the construction phase should be concrete and detailed on the basis of accurate information on a given project, which may not be available in the planning phase. Therefore, the results of previous studies may be limited in estimating the schedule for a construction project that is already in progress. According to other studies tackling productivity in construction, the equipment inputted into a construction project is a very important factor influencing productivity (Han et al. 2006; Hong and Hastak 2007; Luo and Najafi 2007). Thus, it is necessary to analyze the effectiveness and amount of equipment affecting construction project duration.

Core wall construction of high-rise buildings was chosen for the purpose of this study. Functioning as the structure of a high-rise building, core wall is built three to four stories faster than other frame structures. This is considered an important factor in schedule planning (Koo 2003; Kook 2004). Therefore, any delay in core wall construction will greatly affect the overall project duration. Furthermore, because core wall construction is a highly repetitive construction activity, it can be effectively managed by schedule

[1]Assistant Professor, Dept. of Architectural Engineering, Yonsei Univ., Seoul, Korea (corresponding author). E-mail: hong7@yonsei.ac.kr

[2]Visiting Scholar, Div. of Construction Engineering and Management, Purdue Univ., West Lafayette, IN.

[3]Professor, Dept. of Architectural Engineering, Univ. of Seoul, Seoul, Korea.

[4]Associate Professor, School of Architecture, Inha Univ., Incheon, Korea.

Note. This manuscript was submitted on August 16, 2009; approved on October 6, 2010; published online on May 16, 2011. Discussion period open until November 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 137, No. 6, June 1, 2011. ©ASCE, ISSN 0733-9364/2011/6-393–402/$25.00.

estimation. Core wall construction that is optimally managed can present a huge advantage to the total duration of construction.

The objective of this study was to develop a schedule estimation model for core wall construction of high-rise buildings. Unlike existing labor-based schedule estimation methods, the developed schedule estimation model considers both the amount of equipment and labor that have been inputted into the project, which are important factors in construction productivity. A computer simulation technique called CYCLONE (i.e., Cyclic Operation Network) was used in the process of developing this model. According to the study conducted by Yamin and Harmelink (2001), a scheduling model should have the following three characteristics: (1) convenient to use; (2) performs quantitative and qualitative calculations; and (3) allows planners to understand the effect of resource variation on the completion date of a construction project.

It is difficult, however, for a project manager who is not familiar with the CYCLONE method to use it for schedule estimation. Therefore, it is necessary to develop a simple method for project managers that can conveniently predict changes in the resources that have been inputted into a given project (Han et al. 2008). Multiple-regression analysis was conducted in this study on the basis of the CYCLONE simulation results, facilitating the development of a schedule estimation model that project managers can easily perform in their construction projects.

## Research Methodology

To develop a schedule estimation model for the core wall construction of high-rise buildings during the construction phase, three steps were followed, as shown in Fig. 1. In the first step, the process of core wall construction, cycle time per floor (i.e., construction time for one floor), quantity of the material that was used, type of labor and equipment, and duration of activities were identified through an in-depth case study of three high-rise buildings in which core wall construction was used.

In the second step, the CYCLONE model for core wall construction was developed based on the process of core wall construction and resources (e.g., duration and resource input data in CYCLONE) that was analyzed in the first stage. To verify the developed simulation model, a comparative analysis was conducted between the results of case studies identified in the first step and those of the simulation developed in the second step.

In the third step, a multiple-regression model, an easy method often used to predict the performance of a construction project, was developed for project managers who may not be familiar with the CYCLONE method. To collect data for the regression analysis, data generation was conducted using the CYCLONE model developed in the second step. The data set on the cycle time and the resources used (e.g., labor and equipment) per floor of core wall construction was obtained through the results of the data generation. Finally, with the use of this data set, a schedule estimation model for core wall construction during the construction phase was developed. The feasibility of the schedule estimation model and its applicability were verified by applying the developed model to an actual high-rise building project.

### Case Study of Core-Wall Construction

In a high-rise construction project, core wall construction is a very important process because it is a crucial factor in the success of the project, not only in terms of the structural aspect of the building, but also in terms of schedule estimation. As described in the previous section, a case study based on three actual construction cases was conducted to analyze the core wall construction method, construction process, cycle time, quantity of materials used, resources, and duration of each activity. An overview of the core wall construction that was analyzed as a case study is shown in Table 1. Cases A, B, and C refer to 41-, 39-, and 45-story buildings, respectively. (1) Case A has 110,696.30 $m^2$ gross floor area, 500.40 $m^2$ core area, and took 12 months to complete. (2) Case B has 81,884.00 $m^2$ gross floor area, 336.20 $m^2$ core area, and took 11 months to complete. (3) Case C has 214,500.00 $m^2$ gross floor area, 679.80 $m^2$ core area, and took 10 months to complete.

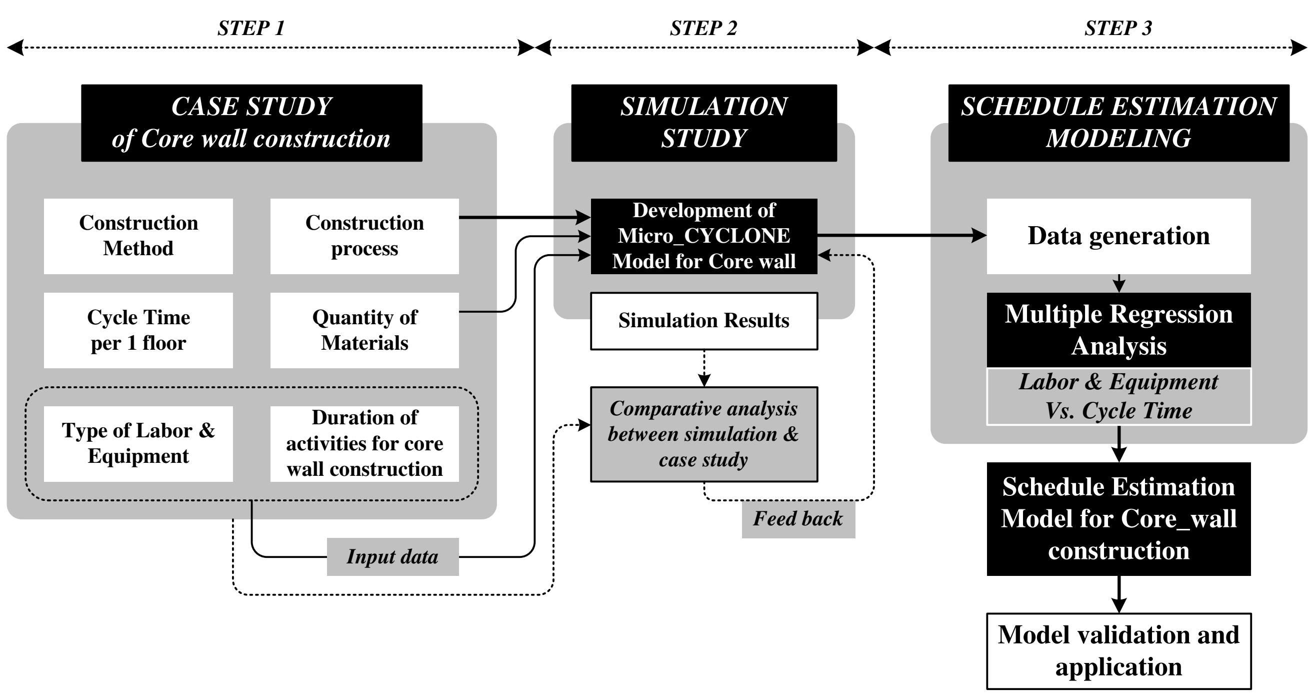


**Fig. 1.** Research framework



J. Constr. Eng. Manage., 2011, 137(6): 393-402

**Table 1.** Case Study Introduction

| Case | Categories | | | | Core wall materials | | |
|---|---|---|---|---|---|---|---|
| | Stories | Gross floor area ($m^2$) | Core area ($m^2$) | Duration[a] | Form ($m^2$) | Rebar (ton) | Concrete ($m^3$) |
| A | 41 | 110,696.30 | 500.40 | 12 | 31,863.70 | 532.20 | 4,979.00 |
| B | 39 | 81,884.00 | 336.20 | 11 | 27,310.60 | 535.00 | 5,226.90 |
| C | 45 | 214,500.00 | 679.80 | 10 | 64,358.62 | 1,747.60 | 13,477.00 |

[a]Construction time for core wall construction (month).

Moreover, the materials used for constructing the core wall in each case are as follows: (1) Case A has 31,863.70 $m^2$ form, 532.20 tons rebar, and 4,979.00 $m^3$ concrete; (2) Case B has 27,310.60 $m^2$ form, 535.00 tons rebar, and 5,226.90 $m^3$ concrete; and (3) Case C has 64,358.62 $m^2$ form, 1,747.60 tons rebar, and 13,477.00 $m^3$ concrete.

In general, there are two construction methods for core wall construction. Typically, core wall construction has been conducted using a tower crane and a form, but recently, the auto climbing system (ACS) form has been widely used. The ACS form is known to offer superior schedule reduction and safety compared to the more traditional method. In addition, because it offers greater quality performance in construction, the ACS form is frequently used in high-rise construction projects. Moreover, because the ACS form is less susceptible to climate changes, it can allow the project to continue even during bad weather conditions, which is very advantageous for schedule estimation. Owing to these strengths, approximately 50% of the 60 high-rise buildings in Korea currently being constructed or already completed use the ACS form, whereas only 28% use a traditional method (Kim et al. 2007). Moreover, the ACS form was used in the three cases analyzed in the present case study. Results of the analysis of the construction process, resource, and duration of each activity were discussed in the following.

## *Simulation Study for Schedule Estimation*

### Simulation Methodology for Schedule Estimation

As described previously, many previous studies on estimating the schedule of repetitive construction projects focus on the following three elements (Ashley 1980; Birrell 1980; Eldin and Senouci 1994; El-Rayes and Moselhi 1998; Kavanagh 1985; Moselhi and El-Rayes 1993; Reda 1990; Russell and Caselton 1988; Selinger 1980):

1. Activity;
2. Crew queuing time and number of crews; and
3. Continuous resource utilization.

Therefore, the simulation methodology for estimating the schedule of core wall construction, which is a repetitive construction process, should consider the previously mentioned three elements in scheduling. In general, computer simulations allow the user to evaluate a variety of scenarios according to changes in resources (Han et al. 2006). CYCLONE, developed by Halpin in 1973, is one of the most widely used computer simulation methods for construction projects (Hong and Hastak 2007; Luo and Najafi 2007). The CYCLONE method is based on deterministic or stochastic variables that use the resources and their interactions, and offers graphic representations to the user (Hong and Hastak 2007; Luo and Najafi 2007). Moreover, CYCLONE's functions, aside from the three scheduling elements (activity, crew queuing time and number of crews, and continuous resource utilization) in repetitive construction projects, can allow the user to analyze the productivity and cycle time according to the inputted equipment. Therefore, a simulation analysis of core wall construction was conducted in this study by using CYCLONE. Detailed information, including the basic modeling elements of CYCLONE, are shown in Fig. 2 and Halpin and Riggs (1992).

### Modeling of Core Wall Construction Process

Three previously discussed high-rise buildings (Table 1) were analyzed for modeling of the core wall construction process of high-rise buildings. According to the results of the analysis, the construction process generally consists of seven independent cycles. First Cycle: disassembly of the gang form and installation of the rebar (Nodes 5 to 13 in Fig. 2); Second Cycle: ACS form climbing (Nodes 15 to 19 in Fig. 2); Third Cycle: installation of the form (Nodes 20 to 21 in Fig. 2); Fourth Cycle: checking the vertical adjustment of the gang form (Nodes 22 to 24 in Fig. 2); Fifth Cycle: concrete placement (Nodes 25 to 32 in Fig. 2); Sixth Cycle: concrete cure and pulling up of the rebar (Nodes 33 to 38 in Fig. 2); and Seventh Cycle: checking the strength of the concrete (Nodes 39 to 40 in Fig. 2). As shown in Fig. 2, the CYCLONE model for core wall construction is developed using modeling elements of CYCLONE with the seven previously described cycles.

### Construction Simulation

**Data Collection** Simulation using CYCLONE requires as input data the duration data of each activity (Combi and Normal in Fig. 2) and the number of resources that comprise each queen node (Fig. 2). The stochastic and deterministic methodologies were used to calculate the duration input data for each Normal and Combi activity.

Table 2 shows the duration of each activity. Nodes 7, 11, 16, 19, 21, 28, 32, 35, and 38 are the durations that were calculated using the stochastic methodology, based on the results of the analysis of the three cases. Triangular distribution was used for the calculation, based on the construction duration of the activities per cycle in the three cases. According to AbouRizk et al. (1994), it is appropriate for the construction simulation input data to follow the beta distribution. It was impossible to follow the beta distribution, however, owing to the practical difficulty (e.g., difficulty in obtaining the number of samples) of calculating the duration of the activities in the core wall construction of each floor in the three analyzed cases. On the other hand, triangular distribution is not largely affected by the number of samples in the data, and its calculation is simple, thereby making the collection of data easy and accurate (Back et al. 2000; Moder et al. 1983; Hong and Hastak 2007). Owing to these characteristics, triangular distribution was used in this study to calculate the input data. Table 2 shows that it will most likely take 9 h to install the rebar (Node 7) and 6 h to disassemble the gang form (Node 11). Meanwhile, because it is not feasible to use the stochastic methodology for Nodes 24 and 40 owing to absence of data, the deterministic methodology was used instead, based on the results of interviews with field project managers. As shown in Table 2, it took approximately 1 h to check the vertical adjustment of the form (Node 24).

The resource input data were collected by calculating the average value of the labor and equipment that were inputted into the three analyzed cases. The results are shown in Table 3. The results of the case study show that, with regard to the form labor crew,



J. Constr. Eng. Manage., 2011, 137(6): 393-402

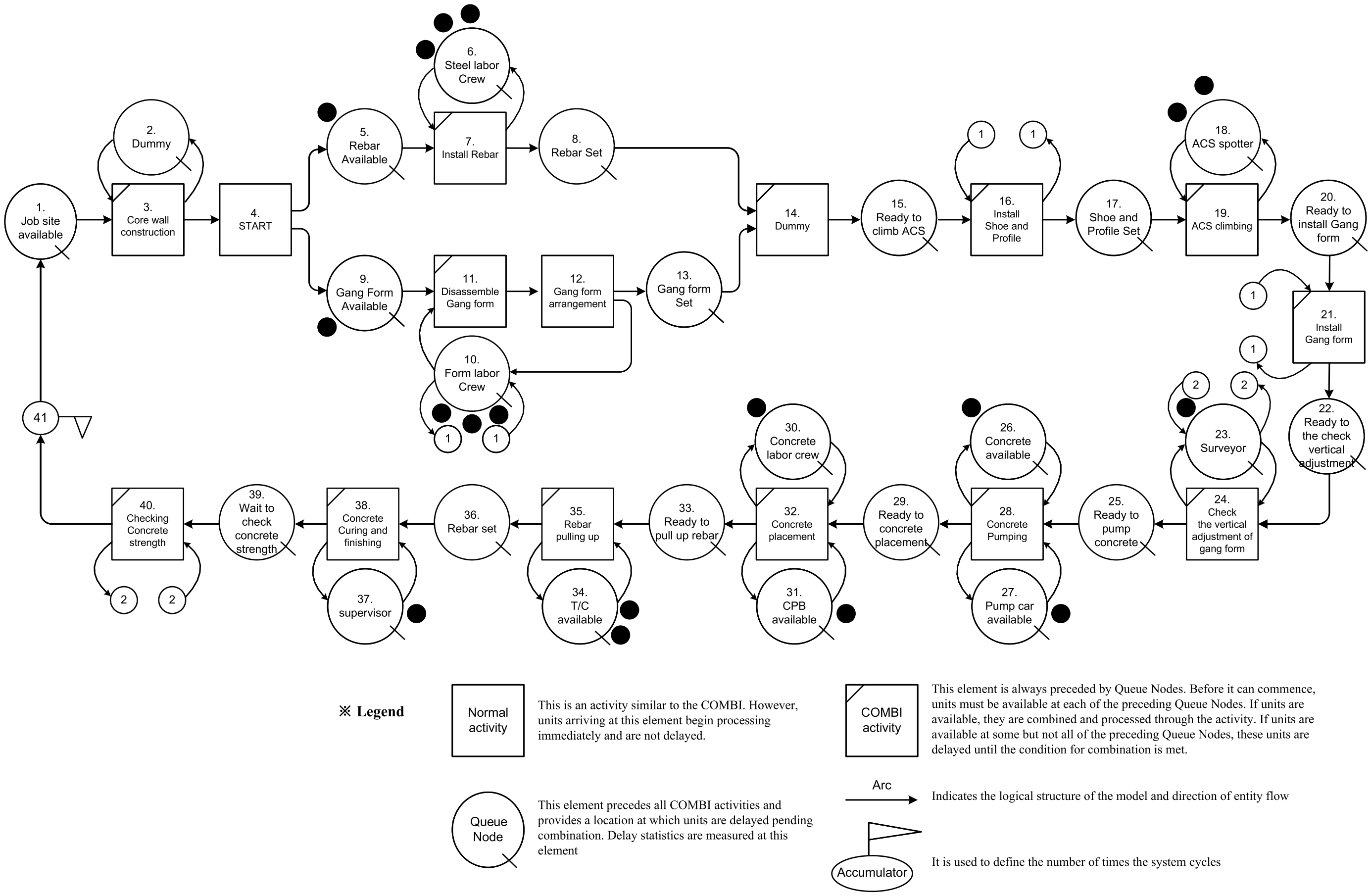


**Fig. 2.** CYCLONE model for core wall construction (Data modeled using WebCYCLONE, Halpin and Riggs 1992)

**Table 2.** Duration Input Data for Simulation

| Node | Work task | Duration (h) Minimum | Most likely | Maximum |
|---|---|---|---|---|
| 7 | Install rebar | 8.00 | 9.00 | 10.00 |
| 11 | Disassemble gang-form | 5.00 | 6.00 | 7.00 |
| 16 | Install shoe and profile | 5.00 | 6.00 | 7.00 |
| 19 | ACS form climbing | 6.00 | 7.00 | 8.00 |
| 21 | Install gang form | 13.00 | 14.00 | 15.00 |
| 24 | Check the vertical adjustment | 1.00[a] | | |
| 28 | Concrete pumping | 1.00 | 1.50 | 2.00 |
| 32 | Pour concrete | 6.00 | 6.50 | 7.00 |
| 35 | Pull up rebar | 3.00 | 3.50 | 4.00 |
| 38 | Concrete curing and finishing | 15.00 | 16.00 | 17.00 |
| 40 | Check the strength of concrete | 1.00[a] | | |

[a]Constant duration input for the entire project.

**Table 3.** Resource Input Data for the Simulation

| | Resource Type | Amount of labor and equipment |
|---|---|---|
| Labor | Steel crew at Queue 6 | 3 crew |
| | Form crew at Queue 10 | 3 crew |
| | Concrete crew at Queue 30 | 1 crew |
| | ACS spotter at Queue 18 | 2 laborers |
| | Surveyor at Queue 23 | 1 laborers |
| Equipment | Pump car at Queue 27 | 1 each |
| | CPB at Queue 31 | 1 each |
| | TC at Queue 34 | 2 each |

which is the representative labor source, three crews on average were hired for the project. This form labor crew consisted of a total of 10 laborers: (1) one supervisor; (2) four laborers for climbing the ASC form; and (3) five laborers for installing and disassembling the gang form. Furthermore, regarding the steel labor crew, three crews on average were hired for the project, consisting of one supervisor and four laborers for installing the rebar. In addition, one or two ACS spotters and surveyors were also hired for the project. Three types of equipment [pump car, concrete placing boom (CPB), and tower crane (TC)] were used for the core wall construction.

**Simulation Results** Based on the developed CYCLONE model, the resource and cycle time of core wall construction were simulated. Fig. 2 shows that the construction of a one-story core wall requires Queue Node 1 to Accumulator 41. Owing to the repetitive nature of core wall construction, this process continues until the final floor of the construction. Meanwhile, the analyzed case studies show that the core wall in the lower floor is thicker than in the higher stories, therefore requiring more laborers and a longer construction time in the lower floor. Moreover, this difference in core wall thickness necessitates an adjustment of the ACS form, which generates additional activities. However, such activities were not considered in this simulation because they are case-dependent. In fact, the input data for the simulation, shown in Table 2 and 3, are



J. Constr. Eng. Manage., 2011, 137(6): 393-402

**Table 4.** Results of the Simulated Productivity and Cycle Time

| Total simulation time | Cycle number | Productivity per time unit | Cycle time (mean value) |
|---|---|---|---|
| 2993.7 | 100 | 0.033403 (cycles/h) | 29.937 h |

the average values of the duration and input resource per floor of actual case studies. These indicate additional duration and amount of labor owing to the change in the core wall thickness. As such, a simulation was conducted in this study using CYCLONE in which the cycle number was 100 times. As shown in Table 4, 100 simulation cycles required 2,993.7 h, the productivity per time unit was 0.033403 (cycle/h), and the average number of hours required for the construction of a one-floor core wall was 29.937 h.

### Comparative Analysis between Simulation and Case Study

As described previously, the previously analyzed case study results and the results of the simulation were used to determine whether the developed CYCLONE model appropriately represents actual core wall construction cases. As shown in Table 5, Case A used three form crews as labor resources (31.20 laborers for formwork on average), two steel crews (11.90 laborers for installing rebar on average), and one concrete crew (5 laborers for pouring concrete, which is identical for all the floors) on average. As for the equipment resources, Case A used one pump car, one CPB, and two TCs. With such labor and equipment resources, it took 29.06 h on average to construct a one-story core wall in Case A. The simulation results of the developed CYCLONE model show that it took 29.94 h on average to construct a one-story core wall. As shown in Table 5, the difference between the two results was 2.93%. The differences between the results of actual case studies and the simulation for Case B and Case C were 5.69 and 3.18%, respectively. Therefore, it was shown that the developed CYCLONE model effectively reflected the actual core wall construction.

## Schedule Estimation Modeling

Operating the CYCLONE model requires special knowledge. As such, project managers and engineers on the field may find it difficult to utilize this model. As discussed previously, a multiple-regression model that is widely used and easy to operate was developed in this study. A regression method analyzes the relationship between dependent variables and several independent variables, and their effects on each other, through historical data analysis. The regression model has been widely used in studies on project cost and schedule estimation. Because it uses several independent variables that largely affect project costs and schedules, the regression model offers a highly accurate prediction. However, the regression model shows only the partial relationship between dependent variables and several independent variables, because it sometimes omits important independent variables to provide greater explanatory power. For detailed information regarding the regression model, refer to Hair et al. (2006).

**Table 6.** Resource Variation for Data Generation

| Category of resource variation | | | | | |
|---|---|---|---|---|---|
| Labor resource | | | Equipment resource | | |
| Form crew | Steel crew | Concrete crew | Pump car | CPB | TC |
| 3 to 5 team | 2 to 5 team | 1 to 2 team | 1 to 2 each | | 2 to 3 each |

### Data Generation

To perform regression analysis, data generation was conducted using the developed CYCLONE model. The generated data set can be acquired through sensitivity analysis, a function of CYCLONE. Data generation was conducted by analyzing changes in the productivity and mean value of the cycle time according to changes in the labor and equipment resources. The scope of the labor and equipment variation, which would be highly applicable in actual cases, was set by analyzing the results of the case study (Table 5) and the interviews with project managers who carried out each case.

Table 6 shows the resource variation for the data generation. Among the labor resources, the variation scope of the form crew was three to five teams, two to five teams for the steel crew, and one to two teams for the concrete crew. Among the equipment resources, the variation scope of the pump car and CPB was one to two, whereas that of the TC was two to three. Using such changes in resources, this study obtained a data set consisting of a total of 192 data: $3(\text{form crew}) \times 4(\text{steel crew}) \times 2(\text{concrete crew}) \times 2(\text{pump car}) \times 2(\text{CPB}) \times 2(\text{TC})$. Table 7 shows part of the data set.

### Regression Modeling

By using the results shown in Table 7, a regression model capable of controlling the schedule of the core wall construction was developed in this study. The model is based on the possible variables that can be used in the construction phase. The labor and equipment resources that were inputted in the construction phase were chosen as the independent variable, and the cycle time required to construct a one-story core wall was chosen as the dependent variable. Table 8 shows a detailed explanation of each variable, defining three independent variables ($LR^1$, $LR^2$, and $LR^3$) regarding labor resources and another three independent variables ($ER^1$, $ER^2$, and $ER^3$) regarding equipment resources. A total of six independent variables were defined as basic variables. With the basic variables and data set (Table 8), a first linear-regression analysis was conducted. A detailed explanation of this analysis will be offered in the following.

The regression model deduced from the first linear-regression analysis failed to achieve what the study set out to do. The variables

**Table 5.** Comparison of Cycle Time between Simulation and Case Study

| | Categories | | | | | | Cycle time (h) | | Remark[a] |
|---|---|---|---|---|---|---|---|---|---|
| | Labor resource | | | Equipment resource | | | | | |
| Case | Form crew | Steel crew | Concrete crew | Pump car | CPB | TC | Case study | Simulation results | |
| A | 3 (31.20) | 2 (11.90) | 1 (5.00) | 1 | 1 | 2 | 29.06 | 29.94 | 2.93% |
| B | 3 (29.20) | 3 (14.80) | 1 (4.70) | 1 | 1 | 2 | 31.74 | 30.03 | 5.69% |
| C | 4 (43.70) | 5 (25.30) | 1 (5.40) | 1 | 2 | 2 | 24.92 | 24.15 | 3.18% |

Note: The number enclosed in parentheses refers to the mean value in terms of labor unit.
[a]Mean value of case study: $c = (|a - b|/b) \times 100$, where $a$ = case study; $b$ = simulation results; and $c$ = remarks.



J. Constr. Eng. Manage., 2011, 137(6): 393-402

**Table 7.** Results of Data Generation

| Result of data generation | | | | | | | |
|---|---|---|---|---|---|---|---|
| Resource information | | | | | | Productivity information | |
| Labor resource | | | Equipment resource | | | | |
| Number of form crew | Number of steel crew | Number of concrete crew | Number of pump cars | Number of CPBs | Number of TCs | Productivity per unit time | Mean cycle time |
| 3 | 2 | 1 | 1 | 1 | 2 | 0.0334 | 29.9401 |
| 3 | 2 | 1 | 1 | 1 | 3 | 0.0335 | 29.8507 |
| 3 | 2 | 1 | 1 | 2 | 2 | 0.0334 | 29.9401 |
| 3 | 2 | 1 | 1 | 2 | 3 | 0.0334 | 29.9401 |
| 3 | 2 | 2 | 1 | 1 | 2 | 0.0334 | 29.9401 |
| 3 | 2 | 2 | 1 | 1 | 3 | 0.0335 | 29.8507 |
| 5 | 5 | 2 | 2 | 1 | 2 | 0.0476 | 21.0084 |
| 5 | 5 | 2 | 2 | 1 | 3 | 0.0478 | 20.9205 |
| 5 | 5 | 2 | 2 | 2 | 2 | 0.0478 | 20.9205 |
| 5 | 5 | 2 | 2 | 2 | 3 | 0.0477 | 20.9644 |

**Table 8.** Variation for Multiple-Regression Analysis

| Type of variable | | | Explanation | Remark | |
|---|---|---|---|---|---|
| Dependent variables | | | $CY_{Time}$: cycle time per 1 floor | These variables have been used in the first regression analysis | All variables have been used in the second regression analysis |
| Independent variables | Basic variables | Labor resource | $LR^1$: number of form labor crew | | |
| | | | $LR^2$: number of steel labor crew | | |
| | | | $LR^3$: number of concrete labor crew | | |
| | | Equipment resource | $ER^1$: number of pump cars | | |
| | | | $ER^2$: number of CPBs | | |
| | | | $ER^3$: number of TCs | | |
| | Additional variables (variable interaction) | | $AV^1$: $LR^1 \times LR^2$ | | |
| | | | $AV^2$: $LR^1 \times LR^3$ | | |
| | | | $AV^3$: $LR^1 \times ER^1$ | | |
| | | | $AV^4$: $LR^1 \times ER^2$ | | |
| | | | $AV^5$: $LR^1 \times ER^3$ | | |
| | | | $AV^6$: $LR^2 \times LR^3$ | | |
| | | | $AV^7$: $LR^2 \times ER^1$ | | |
| | | | $AV^8$: $LR^2 \times ER^2$ | | |
| | | | $AV^9$: $LR^2 \times ER^3$ | | |
| | | | $AV^{10}$: $LR^3 \times ER^1$ | | |
| | | | $AV^{11}$: $LR^3 \times ER^2$ | | |
| | | | $AV^{12}$: $LR^3 \times ER^3$ | | |
| | | | $AV^{13}$: $ER^1 \times ER^2$ | | |
| | | | $AV^{14}$: $ER^1 \times ER^3$ | | |
| | | | $AV^{15}$: $ER^2 \times ER^3$ | | |

related to labor and equipment resources were not appropriately included in the regression model. Only the form labor crew was included as a variable that affected the cycle time. Therefore, additional variables were generated in this study so that other labor and equipment variables could be included in the regression model. Subsequently, a second regression analysis was conducted. Additional variables were used to offer the researcher a more effective explanation of the relationship between the dependent and independent variables. The methods that can be used to generate additional variables are (1) variable transformations, (2) dummy variables, and (3) variable interaction. The regression model with additional variables, therefore, shows higher adjusted $R^2$ values than the regression model with existing basic variables. Among the three methods generating additional variables, the variable interaction can be used when a certain independent variable has a huge effect on the other independent variables; that is, when the interaction effect (or moderator effect) occurs (Hair et al. 2006). As shown in the first regression analysis, one independent variable (e.g., the form labor crew) had a huge effect on the dependent variables. Therefore, additional variables were generated in this study by using the variable interaction method. This method forms a compound variable by multiplying $X_1$ by $X_2$, which are entered into the regression equation. The relationship by interaction is represented as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \varepsilon_n \quad (1)$$



J. Constr. Eng. Manage., 2011, 137(6): 393-402

where $\beta_0$ = constant; $\beta_1 X_1$ and $\beta_2 X_2$ = linear effects of $X_1$ and $X_2$; and $\beta_3 X_1 X_2$ = interaction effect of $X_1$ and $X_2$ (Hair et al. 2006). Table 8 shows the 15 additional variables used in this study ($AV^1$ to $AV^{15}$). With the six basic independent variables and 15 additional independent variables shown in Table 8, a second regression analysis (nonlinear regression) was conducted.

## Multiple-Regression Analysis

The first regression analysis, a linear regression, used six basic variables (Table 8). The second regression analysis, a nonlinear regression, used a total of 21 independent variables (six basic independent variables and 15 additional variables). In regression analysis that includes additional variables, researchers have to proceed by trial and error many times, constantly assessing the improvement of the model's explanation power, which is capable of representing the actual data in the regression analysis and meeting the research objective. SPSS 12.0 was used for the regression analysis in this study. As shown in Tables 9 and 10, the first regression model is as follows:

$$\mathrm{CY_{Time}} = 61.484 - 5.874 \times \mathrm{LR}^1 \tag{2}$$

where the adjusted $R^2$ value was 0.597 and Eq. (2) has a coefficient significant of the dependent variables at the 99% level.

As shown in Eq. (2), the results of the first regression analysis show only the relation between the cycle time and $\mathrm{LR}^1$ (the form labor crew), thus failing to achieve the aim of this study: to estimate the cycle time reflecting the labor and equipment resources simultaneously. As such, the second regression analysis was conducted in this study using additional variables.

As shown in Table 9, the results of the second regression analysis revealed that the adjusted $R^2$ value increased by 8.8%, from 0.597 to 0.685, and the standard error of the estimation dropped from 13.877 to 2.085. Moreover, six basic variables were applied to the variables that comprised the second regression model (e.g., $\mathrm{AV}^1 = \mathrm{LR}^1 \times \mathrm{LR}^2$, $\mathrm{AV}^3 = \mathrm{LR}^1 \times \mathrm{ER}^1$, $\mathrm{AV}^2 = \mathrm{LR}^1 \times \mathrm{LR}^3$, $\mathrm{AV}^4 = \mathrm{LR}^1 \times \mathrm{ER}^2$, and $\mathrm{AV}^5 = \mathrm{LR}^1 \times \mathrm{ER}^3$), thus achieving the aim of this study. Because the variable interaction often includes the same independent variables in its regression equation, it is thus essential to check the multicollinearity among the independent variables. In general, either the variance inflation factor (VIF) or the condition index is used for checking the multicollinearity, where the cutoff thresholds of VIF and the condition index are a VIF value of 10 and a condition index value that is less than 15 points, respectively (Hair et al. 2006; Liou and Huang 2008).

As shown in Table 10, the VIF value in the second regression model was 1.219 to 1.424, and all the condition indices were less than 12, showing that there was no multicollinearity among the variables. Through this process, the second regression model was selected in this study, expressed in Eq. (3):

$$\begin{aligned}\mathrm{CY_{Time}} = 37.791 &- 0.144 \times \mathrm{AV}^1 - 0.309 \times \mathrm{AV}^3 - 0.311 \times \mathrm{AV}^2 \\ &- 0.312 \times \mathrm{AV}^4 - 0.516 \times \mathrm{AV}^5\end{aligned} \tag{3}$$

For example, if the additional variables are converted to basic variables and the crew unit to labor unit, the equation can be represented as follows:

$$\begin{aligned}\mathrm{AV}^1 &= \mathrm{LR}^1 \times \mathrm{LR}^2 = \text{Form Labor Crew} \times \text{Steel Labor Crew} \\ &= \frac{\text{FormLabor}}{10} \times \frac{\text{SteelLabor}}{5}\end{aligned} \tag{4}$$

As such, the final Eq. (5) was formulated in this study:

$$\begin{aligned}\mathrm{CY_{Time}} = 37.791 &- 0.144 \times \frac{\mathrm{FL}}{10} \times \frac{\mathrm{SL}}{5} - 0.309 \times \frac{\mathrm{FL}}{10} \times \mathrm{PC} \\ &- 0.311 \times \frac{\mathrm{FL}}{10} \times \frac{\mathrm{CL}}{5} - 0.312 \times \frac{\mathrm{FL}}{10} \times \mathrm{CPB} \\ &- 0.516 \times \frac{\mathrm{FL}}{10} \times \mathrm{TC}\end{aligned} \tag{5}$$

Where FL = form labor; SL = steel labor; CL = concrete labor; PC = pump car; CPB = concrete placing boom; and TC = tower crane.

## Validation

An actual high-rise building case was used for validation. As shown in Table 11, the actual eight-month data (December 2001, February through June, August, and September 2002) pertaining to the resource input and cycle time for one floor, which were relatively

**Table 9.** Model Summary

| Model | Independent variables | $R$ | $R^2$ | Adjusted $R^2$ | Standard error of the estimate | Improvement of adjusted $R^2$(%) |
|---|---|---|---|---|---|---|
| First regression | 6[a] | 0.773 | 0.597 | 0.597 | 13.877 | — |
| Second regression | 21[b] | 0.833 | 0.693 | 0.685 | 2.085 | 8.8% |

[a] $\mathrm{LR}^1$, $\mathrm{LR}^2$, $\mathrm{LR}^3$, $\mathrm{ER}^1$, $\mathrm{ER}^2$, and $\mathrm{ER}^3$ in Table 9.
[b] All independent variables in Table 9.

**Table 10.** Coefficients and Collinearity Statistics

| Model | | Unstandardized coefficients | | Standardized coefficients | | | Collinearity statistics | | |
|---|---|---|---|---|---|---|---|---|---|
| | | B | Standard error | Beta | $t$ | Sig.[a] | Tolerance | VIF | Condition index |
| First regression | Constant | 61.484 | 0.865 | | 71.048 | 0.000 | | | 1.000 |
| | $\mathrm{LR}^1$ | −5.874 | 0.139 | −.773 | −42.117 | 0.000 | 1.000 | 1.000 | 4.075 |
| Second regression | Constant | 37.791 | 0.640 | | 59.036 | 0.000 | | | 1.000 |
| | $\mathrm{AV}^1$ | −0.144 | 0.031 | −0.209 | −4.641 | 0.000 | 0.810 | 1.235 | 7.488 |
| | $\mathrm{AV}^3$ | −0.309 | 0.070 | −0.198 | −4.421 | 0.000 | 0.820 | 1.219 | 7.488 |
| | $\mathrm{AV}^2$ | −0.311 | 0.070 | −0.200 | −4.458 | 0.000 | 0.820 | 1.219 | 7.700 |
| | $\mathrm{AV}^4$ | −0.312 | 0.070 | −0.200 | −4.465 | 0.000 | 0.820 | 1.219 | 9.709 |
| | $\mathrm{AV}^5$ | −0.516 | 0.062 | −0.401 | −8.287 | 0.000 | 0.702 | 1.424 | 11.958 |

[a] $P < 0.001$.



J. Constr. Eng. Manage., 2011, 137(6): 393-402

**Table 11.** Validation of Schedule Estimation Model

| Duration | Floor | Actual high-rise building case Resource[a] Form labor | Steel labor | Concrete labor | Pump car | CPB | TC | Cycle time | Scheduling model Cycle time | Remark |
|---|---|---|---|---|---|---|---|---|---|---|
| December 2001 | 6–13 (8) | 35.58 | 21.50 | 5.42 | 2 | 1 | 2 | 28.125 | 27.408 | 2.55 |
| February 2002 | 16–21 (6) | 40.70 | 34.12 | 5.20 | 2 | 1 | 2 | 26.100 | 24.490 | 6.17 |
| March 2002 | 22–29 (8) | 32.88 | 18.10 | 4.33 | 2 | 1 | 2 | 29.813 | 28.740 | 3.60 |
| April 2002 | 30–37 (8) | 29.50 | 20.75 | 3.88 | 2 | 1 | 2 | 30.375 | 29.529 | 2.78 |
| May 2002 | 38–45 (8) | 34.37 | 20.87 | 4.00 | 2 | 1 | 2 | 29.000 | 28.127 | 3.01 |
| June 2002 | 46–53 (8) | 31.50 | 41.50 | 3.50 | 2 | 1 | 2 | 28.286 | 27.160 | 3.98 |
| August 2002 | 57–63 (7) | 40.00 | 23.57 | 5.14 | 2 | 1 | 2 | 27.643 | 25.948 | 6.13 |
| September 2002 | 64–68 (5) | 37.50 | 19.60 | 3.60 | 2 | 1 | 2 | 27.800 | 27.477 | 1.16 |

[a]Mean value of each floor: c = $(|a-b|/b) \times 100$, where $a$ = cycle time; $b$ = modeled cycle time; $c$ = remark.



uniform, were applied to the schedule estimation model [e.g., Eq. (5)] for the core wall process.

As shown in Table 11, five to eight floors were constructed per month, excluding holidays and unworkable days owing to weather condition. In March 2002, a total of eight floors from 22 to 29 stories were constructed, and the mean quantity of labor resources per floor was 32.88 form laborers, 18.10 steel laborers, and 4.33 concrete laborers. Moreover, there were two pump cars, one CPB, and two TCs. Based on these resources, the mean cycle time for the construction of one floor was 29.813 h. On the basis of this resource data set, the cycle time by the schedule estimation model was 28.740 h. The difference between the cycle time in the real case and the cycle time estimated by the schedule estimation model was 3.6%, therefore the model was highly accurate. Furthermore, the eight stories (i.e., from the 38th to the 45th floors), which were constructed in May 2002, took an average of 29 h per floor to construct. The result of the schedule estimation model under the same conditions was 28.127 h. The difference between the case and the model is 3.01%. The other differences are 2.55% (December 2001), 6.17% (February 2002), 2.78% (April 2002), 3.98% (June 2002), 6.13% (August 2002), and 1.16% (September 2002). These results show that the developed schedule estimation model is highly reliable.

Despite the comparative-analysis results shown in Table 11, the root-mean-square error (RMSE) value was also analyzed in the study to obtain a more objective validation. The RMSE value, in general, is a goodness-of-fit index for measuring the accuracy of proposed models. The value is derived on the basis of the deviation between the observed value in the case study and the predicted value by the schedule estimation model for the core wall process. When the RMSE value is zero, the prediction accuracy of the developed model can be regarded as perfect. When the RMSE value is greater than one, the accuracy of the developed model is considered not good (Hair et al. 2006; Han et al. 2007; Ling et al. 2001). In general, the RMSE value is expressed as Eqs. (6) and (7):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\hat{x}_i)^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2}} \tag{6}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{7}$$

where $x_i$ = observed value; $\hat{x}_i$ = predicted value; $\bar{x}$ = mean of observed values; and $n$ = number of data considered. Using Eqs. (6) and (7), the RMSE value between the average cycle time per each month in Table 11 and the proposed cycle time drawn by the schedule estimation model was calculated. As shown in Table 12, the RMSE value among two cycle times was 0.891. In addition, because this value is smaller than 1, the schedule estimation model seems highly reliable.

**Effect of the Developed Model** To verify the effectiveness and usability of the proposed model, it was compared to a model developed based on methodologies used in existing studies. Existing studies often used a labor resource-driven scheduling method, and many other studies also used a regression methodology. Therefore, this study developed a schedule estimation model based on the regression analysis of the relation between the labor resource (i.e., form labor, steel labor, and concrete labor) and cycle time, using the 83 data that were collected from the three cases (Cases A, B, and C in Table 1). Eq. (8) shows the developed regression model, where the adjusted $R^2$ value was 0.476, and the model had a coefficient significant to the dependent variables at 99% level:

$$\text{Cycle Time} = 33.184 - 0.749 \times \text{Steel Labor} + 0.304 \times \text{Form Labor} \tag{8}$$

Fig. 3 shows the result of the comparison between the simulation-based regression model [i.e., Eq. (5)], proposed in this study and the regression model based on the methodologies of existing studies [i.e., Eq. (8)]. For a comparison, the amounts of resources from actual cases used in Table 11 were entered into the two models to estimate the cycle time. As shown in Fig. 3, the regression model

**Table 12.** Result of RMSE Value Calculation

| Month | Case Study Actual cycle time | Scheduling model Forecasted cycle time | Deviation |
|---|---|---|---|
| December 2001 | 28.125 | 27.408 | 0.717 |
| February 2002 | 26.100 | 24.490 | 1.610 |
| March 2002 | 29.813 | 28.740 | 1.073 |
| April 2002 | 30.375 | 29.529 | 0.846 |
| May 2002 | 29.000 | 28.127 | 0.873 |
| June 2002 | 28.286 | 27.160 | 1.126 |
| August 2-02 | 27.643 | 25.948 | 1.695 |
| September 2002 | 27.800 | 27.477 | 0.323 |
| Sum | 227.142 | 218.879 | 8.263 |
| Mean | 28.393 | 27.360 | 1.033 |
| RMSE | | | 0.891 |

Deviation = $|a-b|$, where $a$ = actual cycle time; and $b$ = forecasted cycle time.



J. Constr. Eng. Manage., 2011, 137(6): 393-402

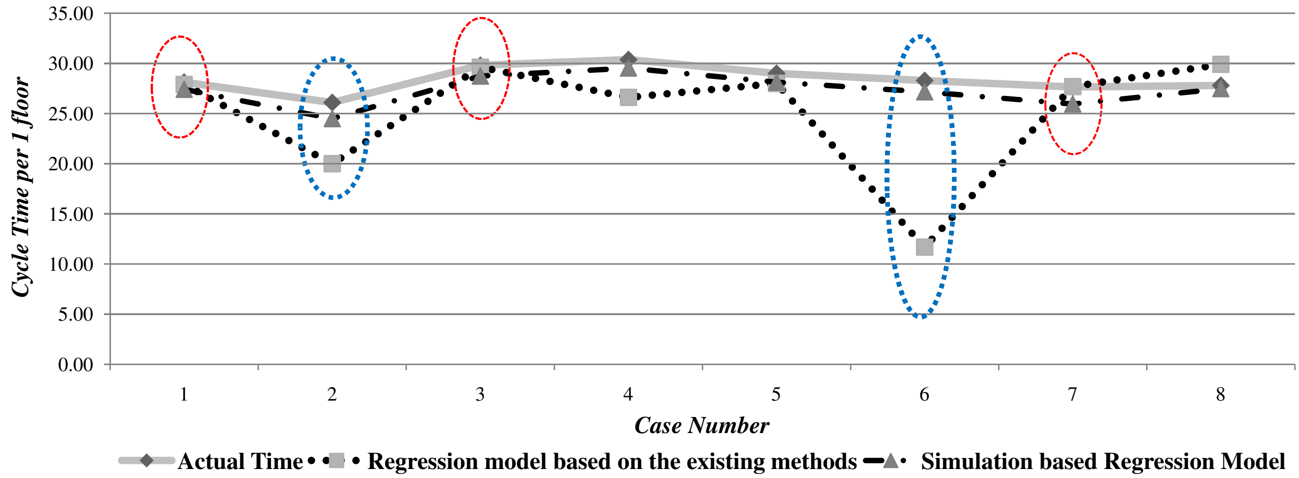


**Fig. 3.** Comparison results

based on the methodologies of existing studies showed superior estimation power in some cases, such as in Cases 1 (December 2001), 3 (March 2002), and 7 (August 2002). Overall, however, the simulation-based regression model showed a smaller deviation value between the estimation and actual value. This is particularly true in Cases 2 (February 2002) and 6 (June 2002), in which the regression model based on the methodologies of existing studies showed a huge deviation from the actual value. Therefore, despite insufficient cases for comparison, the proposed model is expected to offer more reliable estimation than the estimation model based on existing methodologies.

This result is related to the data constitution used in the developing process of each model. The actual data acquired from the case analysis reflect the uncertainty of the construction project (i.e., weather, labor strikes, and labor congestions and idleness). Therefore, there exists an outlier in the actual data, and data construction becomes uneven in the presence of variance. However, in this study, using the simulation model developed based on the actual data results in productivity rates that are closer to ideal and with less uncertainty as simulations are conducted (Halpin and Riggs 1992). Therefore, the data set generated by simulation is close to ideal productivity and manifests some difference from the actual data in evenness. The data set generated by the CYCLONE model is superior in consistency than the actual data set. Fig. 3 shows that the simulation-based regression model developed based on this data set is expected to estimate construction time more correctly.

This study proposed a schedule estimation model [i.e., Eq. (5)] that considers both labor and equipment by combining simulation and regression. Unlike the existing labor resource-driven scheduling methods, it shows the effect of equipment on construction time, so it is expected to offer more effective scheduling.

Using the schedule estimation model developed in this study, a project manager can easily predict construction cycle time. Moreover, if there is a limit in the input resources arising from field conditions such as input cost, the project manager can adjust the cycle time by freely changing the amount of input resources, depending on the field conditions.

## Conclusion

Schedule estimation is very important in the construction phase because it can enable the construction project manager to prepare for a number of unexpected problems that may occur. Therefore, this study aimed at developing a schedule estimation model that considered both the labor and equipment resources during the construction phase. Core wall construction, one of the most important construction activities in terms of schedule planning for high-rise building construction, was selected in this study.

To develop a schedule estimation model, this study used a combination of the simulation method and the regression method, subsequently verifying the simulation-based regression model developed by combining the two methods. The result shows more reliable data than those obtained from existing scheduling estimation methods that use regression alone. The schedule estimation model developed in this study shows the changes in the cycle time per core wall floor according to the changes in the input labor (form, steel, and concrete labor) and equipment (pump car, CPB, and TC) resources. Therefore, when unexpected delays occur during the construction phase of core wall high-rise buildings, the project manager or engineer can easily, quickly, and accurately perform schedule estimation using the developed model.

In the process of validating the proposed schedule estimation model, this study used the data of a floor from one project. However, it is necessary that future studies perform a more generalized validation of the model using several projects. Moreover, the changes in the cost owing to changes in resources when using this schedule estimation model could not be considered in this study. The occurrence of interfering factors in the existing labor and equipment resources, such as the necessity for additional labor and equipment resources, could not be considered. Therefore, further studies are required to consider both the cycle time and cost that arise from changes in the resources. Further studies should also be conducted on the effect of interfering factors on the allocation of equipment and resources owing to additional resources.

## Acknowledgments

This work was supported by the Yonsei University Research Fund of 2009.

## References

AbouRizk, S., Halpin, D., and Wilson, J. (1994). “Fitting beta distributions based on sample data.” *J. Constr. Eng. Manage.*, 120(2), 288–305.

Ashley, D. B. (1980). "Simulation of repetitive-unit construction." *J. Constr. Div.*, 106(2), 185–194.

Back, W., Boles, W., and Fry, G. (2000). "Defining triangular probability distributions from historical cost data." *J. Constr. Eng. Manage.*, 126(1), 29–37.

Birrell, G. S. (1980). "Construction planning—Beyond the critical path." *J. Constr. Div.*, 106(3), 389–407.

Eldin, N. N., and Senouci, A. B. (1994). "Scheduling and control of linear projects." *Canadian J. Civ. Eng.*, 21(2), 219–230.

El-Rayes, K. (2001). "Object-oriented model for repetitive construction scheduling." *J. Constr. Eng. Manage.*, 127(3), 199–205.

El-Rayes, K., and Moselhi, O. (1998). "Resource-driven scheduling of repetitive activities on construction projects." *Constr. Manage. Econ.*, 16(4), 433–446.

Hair, J., Black, W., Babin, B., Anderson, R., and Tatham, R. (2006). *Multivariate data analysis*, 6th Ed., Pearson Education, Upper Saddle River, NJ, 169–269.

Halpin, D. W., and Riggs, L. S. (1992). *Planning and analysis of construction operations*, Wiley, New York.

Han, S., Hong, T., and Lee, S. (2008). "Production prediction of conventional and GPS-based earthmoving systems using a simulation methodology and multiple regression analysis." *Canadian J. Civ. Eng.*, 35(6), 574–587.

Han, S., Kim, D., and Kim, H. (2007). "Predicting profit performance for selecting candidate international construction project." *J. Constr. Eng. Manage.*, 133(6), 425–436.

Han, S., Lee, S., Hong, T., and Chang, H. (2006). "Simulation analysis of productivity variation by GPS implementation in earthmoving operations." *Canadian J. Civ. Eng.*, 33(9), 1105–1114.

Hong, T., and Hastak, M. (2007). "Simulation study on construction process of FRP bridge deck panels." *Autom. Constr.*, 16(5), 620–631.

Hyari, K., and El-Rayes, K. (2006). "Optimal planning and scheduling for repetitive construction projects." *J. Manage. Eng.*, 22(1), 11–19.

Kavanagh, D. P. (1985). "SIREN: A repetitive construction simulation model." *J. Constr. Eng. Manage.*, 111(3), 308–323.

Kim, T., Jin, L., Shin, Y., Cho, S., and Kang, K. (2007). "An analysis of application by formwork in concrete structural frame work for tall building in Korea." *Annual Conf. on the Korea Institute of Building Construction*, Korea Institute of Building Construction, Seoul, Korea, 387–391.

Koo, S. H. (2003). "A decision-making process to select system form for core wall in high-rise building construction." M.S. thesis, Hanyang Univ., Seoul, Korea.

Kook, K. H. (2004). "Study on constructability improvement core wall construction method of the high-rise building structure." M.S. thesis, Hanyang Univ., Seoul, Korea.

Ling, S. Y., Pasha, M. F., Doun, C. D., Phoon, C. K., and Liaw, C. Y. (2001). "Determination of optimal and stable prediction parameters values in chaotic time series." *World Water Congress 221*, ASCE, Reston, VA.

Liou, F., and Huang, C. (2008). "Automated approach to negotiations of BOT contracts with the consideration of project risk." *J. Constr. Eng. Manage.*, 134(1), 18–24.

Luo, R. Y., and Najafi, M. (2007). "Productivity study of microtunneling pipe installation using simulation." *J. Infrastruct. Syst.*, 13(3), 247–260.

Moder, J. J., Philips, C. R., and Davis, E. W. (1983). *Project management with CPM, PERT and Precedence diagramming*, 3rd Ed., Van Nostrand Reinhold, New York.

Moselhi, O., and El-Rayes, K. (1993). "Scheduling of repetitive projects with cost optimization." *J. Constr. Eng. Manage.*, 119(4), 681–697.

Nasir, D., McCabe, B., and Hartono, L. (2003). "Evaluating risk in construction-schedule model: Construction schedule risk model." *J. Constr. Eng. Manage.*, 129(5), 518–527.

Okmen, O., and Oztas, A. (2008). "Construction project network evaluation with correlated schedule risk analysis model." *J. Constr. Eng. Manage.*, 134(1), 49–63.

Reda, R. M. (1990). "RPM: Repetitive project modeling." *J. Constr. Eng. Manage.*, 116(2), 316–330.

Russell, A. D., and Caselton, W. F. (1988). "Extensions to linear scheduling optimization." *J. Constr. Eng. Manage.*, 114(1), 36–52.

Selinger, S. (1980). "Construction planning for linear projects." *J. Constr. Div.*, 106(2), 195–205.

Vanhoucke, M. (2006). "Work continuity constraints in project scheduling." *J. Constr. Eng. Manage.*, 132(1), 14–25.

Yamin, R. A., and Harmelink, D. J. (2001). "Comparison of linear scheduling model and critical path method." *J. Constr. Eng. Manage.*, 127(5), 374–381.





J. Constr. Eng. Manage., 2011, 137(6): 393-402