A Selection Methodology of Slab-form Construction Methods in Residential Buildings based on the Simulation and Delphi Techniques

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Abstract
Compared to other operations, formwork depends mostly on manual labor and greatly influences the subsequent and overall processes. The form selection criteria for construction projects in South Korea are based however, not on objective and concrete origins, but on the limited experiences of highly practiced planners or engineers. Also, there are no appropriate selection criteria for the data shared by construction companies. Therefore, this paper aims to offer an objective and concrete methodology by which an appropriate formwork operation for structural works can be selected. Toward this end, the aluminum form, sky-deck form, and AFB methods are among the slab form methods widely used in densely populated regions. The Delphi technique was used for the qualitative items of the criteria and the simulation technique for the quantitative items. Also, the AHP technique was applied for finding variable weights of both qualitative and quantitative items in an integrated model. Through the aforementioned procedure, objective selection criteria were derived. Also, by presenting a case study on the selection of an appropriate operation, which includes emerging technologies that completely lack actual data, a practical application of the proposed methodology is proposed.

Keywords: slab form; Delphi; simulation; AHP; sky-deck; AFB

1. Introduction
1.1 Aim and Objectives
Formwork, one of the most critical structural works among many related works for residential building construction, consists of 60-70% of the overall structural works. Compared to the other operations, formwork is mostly dependent on manual labor, and greatly influences the subsequent processes and the overall construction project. Due to the lack of highly experienced workers in the field and the lack of actual data however, the selection criteria for types of formwork methods that are used for construction projects in South Korea are often based on the limited experiences of planners or engineers. Also, there are no appropriate selection criteria for the data shared by construction companies (Lee et al. 2010; Lee 2011). Therefore, it is necessary to propose a methodology by which the new technologies related to the slab form method and existing slab form methods can be compared and analyzed. There should also be a plan by which one can quantitatively evaluate the characteristics of each method, which can presently only be identified via subjective decisions (Lee 2011). The issues to be considered when selecting the qualitative items of the current types of slab form methods were determined, and performance scores of the selected methods were derived via an evaluation by, and agreement among, professionals, using a survey technique called the Delphi technique. On the other hand, for quantitative items, an evaluation plan for the practical application of the slab form was presented by performing a productivity comparison and unit cost analysis among the selected methods based on the construction simulation technique, WebCyclone, which allows the analysis of new technologies for which there is no actual case for study.

1.2 Methodology and Scope
A survey on formworks in the urban areas of South Korea showed that the slab form was often mixed with other operations and materials. This study targeted the aluminum form and the sky-deck form methods that are commonly used in residential buildings in South Korea, and the AFB (aluminum panel form with a dropping beam) method, which was designated as a new technology in August 2009.
To determine the qualitative items on which there is a lack of previous research, the Delphi technique was used. With the Delphi technique, professionals' distributed opinions can be integrated into one opinion on which most professionals can agree. To determine the quantitative items, the construction simulation technique, WebCyclone, was used, with which feasible results can be estimated, using a small volume of data, to compare and analyze the productivity and unit cost of the three methods.

To integrate and evaluate the qualitative and quantitative items, the AHP (Analytic Hierarchy Process) technique was used, and a weighted value was applied to each item to present the final results of the performance evaluation. The results of the proposed methodology should be able to present the criteria based on which formwork methods can be objectively determined.

2. Literature Review

2.1 Current Status of Concrete Slab Forms

The external and internal wall forms and slab forms which have mainly been used in residential buildings in South Korea since 2000, are the gang form and the aluminum form, respectively. Since buildings have recently been built higher, the sky-deck form is now widely used to construct high-rise buildings with over 30 floors (Kim et al. 2006).

As mentioned, the targets of this study are the aluminum form, sky-deck form, and AFB. Table 1. shows the installation process of AFB, aluminum form and sky-deck.

Table 1. Concrete Slab Forms

| AFB       | Slab corner installation | Drop-beam installation | Deck panel installation |
|-----------|--------------------------|------------------------|-------------------------|

Aluminum Form

| Panel installation | Panel fixation | Shore installation |

Sky-deck

| Panel hoist (crane) | Main beam installation | Panel installation |

The aluminum form has become popular recently as a form that can satisfy new needs for well-qualified construction, enhanced construction efficiency, and reduced construction waste etc. The sky-deck form is commonly used to construct high-rise buildings with over 30 floors. Also, it is a type of system form

for slabs that is one of the table forms. This method implements the filler drop-down method during the removal process to reduce noise during construction in densely populated regions. AFB is the slab and staircase form for residential building projects that is intended to simplify the installation of the aluminum form and remove the form without working plates by lowering the aluminum form down by two steps to the height of the laborers' hands (Lee et al. 2010; Lee 2011).

2.2 Key Researches Related to Slab Forms

In most existing studies on the selection of the slab form, the form method was selected by conducting a survey using qualitative items. In other words, in these key studies, a survey was first conducted on the form selection factors, which were then used to determine and systematically evaluate the decision-making support system. These studies are all case-based, however, and if applied to a method with no case studies, could result in errors during the evaluation. Also, there has been a lack of research that considers cost and productivity among the quantitative items (Zayed et al. 2008).

The research by Kang et al. (2009) presented the productivities of various types of form methods by simulation models reflecting specific construction situations. These results were used as basic information for the establishment of standard working activities of formworks (Kang et al. 2009). The research by Kim et al. (2006) provided the prototype of a decision making model based on CBR (Case-Based Reasoning) through calculating the weights of criteria by AHP (Analytic Hierarchy Process) (Kim et al. 2006). These two researches however, showed a practical limitation for application to general situations of formworks due to the lack of other performance information, excluding the data of productivity and the data based on the specific case. The research by Shin et al. (2008) suggested a methodology for the performance evaluation of several formworks which have especially been used in high rise building construction (Shin et al. 2008). This research provided valuable information of the variable construction performance of slab formworks. However, it was agreed that all results suggested in these two researches were based on the traditional methods such as the euro form or aluminum form and so on. The application limitation of an emerging method to the models is suggested since the data of the emerging method were not sufficient to create an objective model in evaluating the performance. The results of the aforementioned researches show that research that integrates the quantitative and qualitative items is needed to compare and evaluate existing and new methods.

3. Construction Data Collection and Analysis

3.1 Planning for the Delphi Technique Application

The Delphi technique is a series of processes through
which professionals in the fields of each subject present and mediate their opinions repeatedly to devise a consensus. With the use of the Delphi technique in this study, an agreement on the qualitative items was reached by conducting two feedback surveys on issues that were collected from the literature review and interviews with professionals and that are considered during the form method selection process. The Delphi technique was implemented in the first to fourth steps with a total of 27 professionals including site engineers (Lee et al. 2010; Lee 2011).

The survey results were analyzed and the appropriate levels of the corresponding items were determined using the mean value (m) and the quartile deviation (Q), considering the response frequency number below the certain value (f1), and the exceeding response frequency number (f2). In other words, in this paper, the comparison value of the frequency number needed to satisfy the minimum value, and the quartile deviation was used to measure the level of agreement among the participants (Lee 2006; Lee et al. 2010; Lee 2011).

3.2 Evaluation of Qualitative Items

In this paper, the performance levels of the aluminum form, sky-deck form, and AFB methods were compared based on the items that must be considered during the form method selection process, which were derived from the first and second Delphi processes. In the third and fourth Delphi processes, the performance levels of the methods were compared.

Table 2. Results of the Delphi Application

| Descriptions | Specific descriptions | Aluminum form | Sky-deck form | AFB form |
|--------------|----------------------|---------------|---------------|----------|
| Productivity | Overall productivity (P1) | - | - | - |
| Economic feasibility | Labor costs (E1) | - | - | - |
| | Material costs (E2) | - | - | - |
| | Equipment costs (E3) | - | - | - |
| | Supplementary costs (E4) | - | - | - |
| Practical application | Costs on reusable values by the number of stories (P1) | 4.07 | 3.93 | 3.93 | 3.00 |
| | Additional costs on form installation by the level height (P2) | 3.21 | 3.07 | 0.00 | 3.21 | 0.25 |
| Working efficiency | Form productions and assembling (W1) | 3.57 | 3.50 | 1.00 | 3.64 | 0.25 |
| | Concrete bindings (W2) | 3.86 | 4.00 | 0.00 | 4.00 | 0.00 |
| | Form applications on structure type (W3) | 3.64 | 2.43 | 1.00 | 3.79 | 0.25 |
| | Form applications on corners (W4) | 3.57 | 3.79 | 0.25 | 4.00 | 0.00 |
| | Form applications on structure types (W5) | 3.64 | 3.14 | 0.00 | 3.57 | 1.00 |
| | Additional activities for filler supports (W6) | 3.57 | 3.86 | 0.00 | 4.21 | 1.00 |
| | Horizontality conditions of slab forms (W7) | 3.57 | 3.86 | 0.00 | 4.21 | 1.00 |
| Quality | Safety of laborers during form assembly and removal (S1) | 3.00 | 3.36 | 1.00 | 3.36 | 1.00 |
| | Conditions after form removal (S2) | 3.64 | 3.86 | 0.25 | 3.86 | 0.25 |
| | Security of working space (S3) | 3.20 | 2.50 | 3.50 | 1.00 | 3.71 | 1.00 |
| Weathering | Concrete surface quality after form removal (Q1) | 3.57 | 3.71 | 1.00 | 3.71 | 1.00 |
| | Repair of defects (Q2) | 3.57 | 3.57 | 1.00 | 3.71 | 1.00 |
| Environment | Noise of work during form operations (E1) | 2.07 | 2.03 | 0.25 | 3.43 | 1.00 |
| | Vibration during form removal (E2) | 2.29 | 3.01 | 0.25 | 4.36 | 1.00 |

Determination of the level of agreement in the Delphi technique can be categorized into three types: the scope of the quartile, the scope of the relative quartile, and the deviating coefficient. In order to avoid the need to determine the average, and instead determine the scope of the performance scores of the target methods, the scope of the quartile was selected based on the level of agreement. Such an agreement is made if the scope of the quartile results is 1 or less by subtracting the first quartile from the third quartile (Lee et al. 2010; Lee 2011). Table 2. shows the performance score of each method derived from the agreement evaluation method based on the scope of the quartile.

The Delphi technique implementation resulted in the deduction of all selection criteria, quantitative items (Productivity and Economic feasibility) and qualitative items (Practical application, Working efficiency, Operation planning, Safety, Quality, and Environment). Relative scores shown in only the quantitative items were also found as mean values in Table 2. after surveying by the Likert scale (1 is very poor, 2 is poor, 3 is neutral, 4 is good, 5 is very good). The relative scores shown in Table 2. were the comparison results of performances among the three methods by professionals. However, the relative scores of the quantitative items were not determined in the Delphi technique since the relative scores of quantitative items were derived from performance calculation and simulation implementation on an objective basis.

3.3 Evaluation of Quantitative Items

3.3.1 Construction Data Collection

To analyze and compare the productivities of the methods of the aluminum form, sky-deck form, and AFB, the methods were measured by conducting a field study at each corresponding site. Video measurement, stopwatch measurement, and interviews with site personnel were used for the observation and data measurement; the measurement results were used to subcategorize the process of each method. The subcategorized activities and working hours by field observations were used for fundamental input data for the modeling of simulation, using WebCyclone (Lee 2011).

(1) Aluminum form

The aluminum form method was measured by visiting a site located in Daejeon, South Korea. The construction of a residential building was in process on the site, and the removal process on the 9th floor and the slab installation on the 11th floor were targeted for study. Table 3. shows the results of the measurement of the site, where the installation area of the aluminum form was 269.17 m².

The measurement results showed that the total working duration was 60.9 hours, and that the work duration, excluding that of the slab form installation and removal, was derived from the interviews with the site personnel. To compare the differences in productivity among the methods, the productivity of each method was analyzed by applying the same conditions, except for the slab form installation and removal duration (Lee 2011).

(2) Sky-deck form

The sky-deck form method was analyzed by visiting the residential building project site located in Incheon,
South Korea. The slab on the 13th floor was being removed and a slab form was being installed on the 15th floor. Table 4. shows the measurement of the work duration for sky-deck.

(3) AFB

The AFB method was measured by visiting the job site of a residential building construction project in Bucheon, South Korea. The form on the 29th floor was being removed, and a form was being installed on the 31st floor, in a 457.99m² area. Table 5. shows the measurement of the work duration for AFB. The time taken to install the form on the 457.99m² floor area was 51.1 hours (Lee 2011).

3.3.2 Productivity Analysis

The productivity levels of the three methods, the aluminum form, sky-deck form, and AFB, were analyzed by applying the activities and working hours, which were measured from the sites, to the WebCyclone of the construction simulation. Figs.1., 2., and 3. show the diagrams of the modeling of each method for WebCyclone (Lee 2011).

The modeling for the three methods was categorized into four stages: the general preparations, the slab form installation, the slab form removal, and the general closing activities.

The general preparation activities included the guideline setting and wall installation works, whereas the general closing activities were modeled by considering the insulation installation, reinforcing bar placement for the concrete slab, mechanical and electrical works, and concrete pouring; and the productivity levels of the three methods were compared and analyzed by considering the installation and removal of the slab form (Lee 2011).

The working hours of activities for the three methods suggested in Figs.1., 2., and 3. were used as duration values in simulation modeling. Working hours of activities for three methods suggested in Figs.1., 2., and 3. were used as duration values in simulation modeling. According to the research by AbouRizk and Halpin (1992), the beta distribution is best fitted on construction data due to the variable flexibility of the shapes. In order to use the information of the best.

| Activity                        | Equipment     | Working hours (hr.) |
|---------------------------------|---------------|---------------------|
| Setting                         |               | 2.5                 |
| Lifting reinforcing bars for wall| 1 crane       | 1.0                 |
| Installing reinforcing bars in wall|             | 6.0                 |
| Preparing form removal in lower level |         | 0.5                 |
| Removing wall forms in lower level |            | 3.0                 |
| Removing wedge pin in lower level |             | 2.6                 |
| Removing slab forms in lower level |           | 2.5                 |
| Rearranging forms in lower level |             | 2.0                 |
| Delivering forms to next level   |              | 1.5                 |
| Assembling wall forms           |              | 4.5                 |
| Assembling slab forms in corners|              | 2.0                 |
| Installing filler and supports   |              | 4.0                 |
| Assembling slab forms           |              | 4.0                 |
| Laying form oils                |              | 1.5                 |
| Lifting reinforcing bars for slab| 1 crane       | 2.0                 |
| Installing reinforcing bars in slab|          | 9.0                 |
| Installing insulations          |              | 1.8                 |
| Installing Mechanical and Electronics |    | 4.5                 |
| Final investigation             |              | 1.0                 |
| Concrete placing                | 1 concrete pump and 2 gas vibrators | 5.0 |

Total working hours 60.9

| Activity                        | Equipment     | Working hours (hr.) |
|---------------------------------|---------------|---------------------|
| Setting                         |               | 2.5                 |
| Lifting reinforcing bars for wall| 1 crane       | 1.0                 |
| Installing reinforcing bars in wall|             | 6.0                 |
| Preparing form removal in lower level |         | 0.5                 |
| Removing wall forms in lower level |            | 3.0                 |
| Removing wedge pin at prophead in lower level | | 0.8 |
| Removing slab forms in lower level |           | 0.6                 |
| Rearranging forms in lower level |             | 0.6                 |
| Removal of main beams in deck form |          | 0.8                 |
| Lifting forms                   |              | 2.0                 |
| Installing wall forms           |              | 4.5                 |
| Installing drophead and main beams |          | 4.1                 |
| Installing slab panels          |              | 2.2                 |
| Laying form oils                |              | 1.5                 |
| Lifting reinforcing bars for slab| 1 crane       | 2.0                 |
| Installing reinforcing bars in slab|           | 9.0                 |
| Installing insulations          |              | 1.8                 |
| Installing Mechanical and Electronics |    | 4.5                 |
| Final investigation             |              | 1.0                 |
| Concrete placing                | 2 concrete pumps and 4 gas vibrators | 5.0 |

Total working hours 53.4

| Activity                        | Equipment     | Working hours (hr.) |
|---------------------------------|---------------|---------------------|
| Setting                         |               | 2.5                 |
| Lifting reinforcing bars for wall| 1 crane       | 1.0                 |
| Installing reinforcing bars in wall|             | 6.0                 |
| Preparing form removal in lower level |         | 0.5                 |
| Removing wall forms in lower level |            | 3.0                 |
| Removing wedge pin at prophead in lower level | | 0.8 |
| Removing slab forms in lower level |           | 0.6                 |
| Rearranging forms in lower level |             | 0.6                 |
| Removal of main beams in deck form |          | 0.8                 |
| Lifting forms                   |              | 2.0                 |
| Installing wall forms           |              | 4.5                 |
| Installing drophead and main beams |          | 4.1                 |
| Installing slab panels          |              | 2.2                 |
| Laying form oils                |              | 1.5                 |
| Lifting reinforcing bars for slab| 1 crane       | 2.0                 |
| Installing reinforcing bars in slab|           | 9.0                 |
| Installing insulations          |              | 1.8                 |
| Installing Mechanical and Electronics |    | 4.5                 |
| Final investigation             |              | 1.0                 |
| Concrete placing                | 2 concrete pumps and 3 gas vibrators | 5.0 |

Total working hours 50.9
fitted distribution in duration input at WebCyclone, large volumes of raw data are required for its sufficient search. Interviews with site personnel at the job sites revealed that the variance of working hours of each activity was very limited due to the simple and constant nature of the activities (Han et al. 2008; Han et al. 2011). As aforementioned, the duration input information is considered as deterministic duration. This assumption is stated as one of the research limitations in the conclusions.

To calculate the working area per hour, the productivity of the hourly area was evaluated by multiplying the floor area of each site with each result. Table 6. shows the results, which were converted into values for productivity (m²/hr), by multiplying the resulting productivity value (cycle/hr) by the total floor area.

While AFB had the highest estimated productivity (cycle/hr), the sky-deck form had the highest result, which was converted into m²/hr (21.134 m²/hr) by multiplying it by the total work area, followed by AFB at 18.134 m²/hr, and the aluminum form at 8.889 m²/hr.

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3.3.3 Cost Analysis

With the productivity analysis presented above, cost analysis is also required for the performance evaluation of the quantitative items in the suggested model. Costs were divided into four specific costs: labor cost, material cost, equipment cost, and temporary or supplementary cost. All information related to costs was derived from interviews and site observations on the visited job sites. The information which was not identified from job sites was found in the references of Korean standard construction costs.
Tables 7., 8., and 9. show the calculation of labor cost, material cost, and temporary or supplementary cost applied to the three methods, respectively. The material costs and temporary or supplementary costs provided in Table 9. were derived from the information collected from the manufacturers of each method.

4. Application of the Proposed Form Selection Method

4.1 Application of the Weighting Value

The weighting value for each item, which was used to select the form, was calculated via the AHP. AHP calculates a weighting value by hierarchizing multiple evaluation items and determining the relative level of importance of each evaluation item based on pairwise comparison, and offers decision-making guidelines, such as the relative importance of the problems, the priority in the problem-solving process, and the selection of alternatives. In this study, the AHP technique was used for the integrated evaluation of the quantitative and qualitative items. Table 10. shows the weighted values of all items as the results of the AHP analysis (Lee 2011). The total weights shown in Table 10. were normalized for each weight after calculating the stepwise weights. Accordingly, the sum of the total weights was 1.00 and each total weight of each sub item was identified as the value of 1.00. For instance, the total weight of "Overall productivity" was found by Equation (4.1).

Total weight of overall productivity (0.11) = the weight of quantitative item (0.40) x the weight of productivity (0.28) x the weight of overall productivity (1.00)  
Equation (4.1)

4.2 Conversion of the Productivity Analysis Results and the Unit Cost Scores

4.2.1 Conversion of the Productivity Scores

To include the productivity and cost that were analyzed in Chapter 3 among the qualitative items and to allocate them a score, the weighted value of the productivity was calculated using AHP analysis. After finding the total weights of each sub item as shown in Table 10. and Equation (4.1), the score of each sub item based on the total weight is identified as the next step. The objective of the model suggested in this study is to find an appropriate construction method by relative comparison of each method. Accordingly, the relative comparison of the three methods needs to be conducted. The maximum value was considered as the optimistic value in productivity assessment. Thus, each score of each method was converted to relative values on the maximum productivity of the one method.

Table 11. shows the adjusted relative scores for the productivity of the three methods.

Table 11. The Adjusted Productivity Scores

| Method    | Hourly Productivity (m^2/hr) | Adjusted score |
|-----------|-------------------------------|----------------|
| Aluminum form | 8.89                           | 0.41           |
| Sky-deck | 21.72                         | 1.00           |
| AFB | 18.13                         | 0.84           |

Equation (4.2) was used to score the adjusted relative scores of productivity.

The adjusted score of Aluminum form (0.41) = the hourly productivity of aluminum form (8.89) / the maximum value among all productivities (21.134)  
Equation (4.2)

4.2.2 Conversion of the Cost Scores

The cost scores were found following the similar procedure for the productivity scores previously suggested. The difference between cost and productivity scoring was only due to the fact that the adjusted cost relative scores were relatively compared to the minimum value of the costs among the three methods. Table 12. shows the adjusted relative scores for the costs of the three methods. Equation (4.3) was used to score the adjusted relative scores of the costs.

The adjusted score of material cost of Aluminum form (1.00) = the minimum value among all material costs (10.18) / the material cost (8.89) / the maximum value among all productivities (10.18)  
Equation (4.3)
4.3 Results of the Performance Evaluation of the Methods

The performance scores of the qualitative items were derived using the Delphi technique with the professionals mentioned in Chapter 3 and those of the quantitative items were derived using the data calculation and simulation technique. The weighting values, with which the quantitative and qualitative items can be integrated, were calculated by applying AHP to the quantitative and qualitative items.

Table 13. Performance Evaluation Results of the Integration Process

| Specific descriptions | Item | Sub category | Score | Adjusted score | Score | Adjusted score |
|-----------------------|------|--------------|-------|----------------|-------|----------------|
| Qualitative           |      |              |       |                |       |                |
| Safety                |      |              |       |                |       |                |
| Quality               |      |              |       |                |       |                |
| Environment           |      |              |       |                |       |                |

The performance scores of the integrated assessment of quantitative and qualitative items were 0.83, 0.90 and 0.94 out of 1.00 of the sky-deck form and AFB respectively.

These results demonstrate that the AFB method can be selected as the appropriate method by the integrated methodology suggested in this study.

5. Conclusions

In this study, the Delphi technique was used to determine the trends with respect to the issues that are considered in the method selection process in current construction sites. Also, the performance evaluation of, and the agreement on, the qualitative items were based on the evaluation scores by the Delphi technique. The productivity and cost of the quantitative items were analyzed using construction simulation. Furthermore, a pairwise comparison of the quantitative items and the qualitative items that are considered in the form selection process was performed to propose an integrated evaluation result based on the weighting.
value of each item through AHP analysis. The results showed that the performance evaluation score of AFB was highest at 0.94, followed by the sky-deck form at 0.90 and the aluminum form at 0.83.

To consider the current issues for the selection of an appropriate construction method among the various methods, the proposed integrated methodology in this study is significant for providing a methodology which is capable of assisting the decision making for method selection. Also, this methodology can be used for other situations where similar cases exist in the construction industry.

This study has two limitations; (1) a wider variety of data could not be collected due to the difficulty of contacting the professionals and the construction sites where the selected methods were being used, and the difficulty of performing the measurements, (2) the suggested methodologies were evaluated in slab form operations only. Such limitations led to the difficulty of reflecting more conditions on the performance score of each method or even various construction operations, so that despite the considerable difference among the three methods, their performance evaluation scores as presented in this paper did not show marked differences. For simulation implementation, the working hours for each activity were assumed to be constant values and deterministic values due to the lack of sufficient volume of raw datasets collected from job sites. The proposed evaluation methodology is expected to contribute to solving the practical problem in the form selection process in construction fields where planners’ experiences were considered as a critical criterion. The methodologies are also expected to provide an academic contribution to determine and unify the research methodologies for appropriate selections, wherein the lack of objective comparison data leads to a selection based on empirical decisions. Future studies should collect actual construction data and cost-related data from various types of construction sites in order to reflect in the analysis as many conditions as possible from the actual construction sites. Also, future studies must verify the estimated values from the simulation by applying them to a construction project with similar conditions to verify the similarity between the estimated and actual values.

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