A Numerical Value Evaluation Model for the Optimum Design Selection

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Abstract
While VE in South Korea must be performed according to law, there is no standard evaluation method for the design values and value indices, and few studies have been conducted on this topic. The methods that are currently in use convert the function and performance evaluation values to grades. Although these methods allow evaluation factors with different properties to be handled in the same way, they can produce different revaluation results depending on the grade setting. Therefore, for the reasonable and effective improvement of the values of buildings, a reasonable value evaluation model that can produce objective and consistent results is needed. In this study, a value evaluation process that systematizes the building element design evaluation process was proposed. A numerical value evaluation model for calculating the cost, physical performance, workability, and index used in the evaluation process was also proposed. The normalization and linear-transformation theories were applied to the proposed numerical value evaluation model, which produces a value index by conducting value evaluation based on mathematical theories rather than by converting the function and performance to grades, as is currently being performed in the existing methods. Thus, the proposed model is expected to yield reliable and objective evaluation results.

Keywords: value engineering; value evaluation; optimum design; decision-making

1. Introduction
1.1 Background and Purpose
Similarly to the open market, the South Korean construction industry has witnessed soaring competition. Due to an increased awareness and an improvement in their quality of life, the owners and users of buildings now demand higher-quality construction products. Accordingly, the government and the entire construction industry are struggling to gain competitiveness in the global market. Having introduced value engineering (VE) in 2000, the South Korean government has mandated the performance of life cycle cost (LCC) and design reviews for public buildings over a certain size, through which the construction value can be improved and competitiveness of the construction industry can be gained. Due to the misunderstanding of the construction industry, however, which considers VE a simple cost reduction method consisting of related laws, VE is often used as a cost-saving method rather than as a method for improving the construction value (MLTM, 2005; Chun, 2007; Cui, 2009). To address this problem, the South Korean government mandated that the performance index, value index, and value improvement rate of the alternative to the original plan be indicated on the VEL proposal when construction companies propose alternatives through VE for public projects over a certain size. The government, however, did not provide a concrete value evaluation method for calculating the value index (KCVERI, 2008). Accordingly, VE service companies use their own value evaluation methods, which can result in different evaluation results even when the evaluation target is the same, rendering it difficult to guarantee the reliability of the evaluation results. Therefore, to realize reasonable and effective construction value improvement through VE, a standardized value evaluation method that can produce objective and consistent results needs to be proposed.

1.2 Literature Review
After the introduction of VE to the construction industry, many studies on function analysis and the VE process have been carried out, but few studies have been conducted on the calculation of the value index (Choi et al., 2009). In South Korea, the value matrix method (Steward, 2005) by Caltrans (California Department of Transportation) and the Dell’Isola method (Alphonse, 1998) are the two main methods for calculating the value index in design VE. The value
matrix method measures the functional values using the costs and performances of designs, and converts the performances of designs to grades. After the further conversion of the grades to the performance contribution level by multiplying the weight based on the priority-by-factor to the grades, the total performance value is calculated by summing up the results. Then, finally, the value index is calculated by dividing the total performance value by the total cost, and the optimum design is selected based on the value improvement rate. Meanwhile, in the Dell'Isola method, the weight is calculated based on the priority of each factor, and the evaluation values are converted to grades. Later, the optimum design is selected based on the total scores of the weighed values of the evaluation factors and the grade scores by design. While some factors for evaluating buildings are considered better if the score is higher, others are considered better if the score is lower. In this regard, the method of converting the values to grades, which is used by both the value matrix and Dell'Isola methods, is convenient to use. Both methods, however, can produce different evaluation results based on the setting of the grade scope, and it is therefore difficult to expect objective results. In particular, in the Dell'Isola method, the optimum design is selected based on the total scores of the cost and performance evaluation values, and therefore, in such method, the value improvement rate and the design value, which shows the cost-to-performance ratio, cannot be determined.

1.3 Scope and Method

A building has various elements. Thus, the cost and performance of a building can be determined by dividing the cost and performance by each part of the building. Accordingly, the optimum design of an entire building can be achieved by selecting and integrating the optimal designs of all the parts of the building (Yoo et al., 1995). Additionally, the recent development of various types of construction systems and materials has resulted in an exponential increase in combination groups for constructing building elements. Thus, building element construction is becoming more important in the design development phase. This study focuses on the value evaluation process, which systemizes the building element design evaluation process in the design development phase, and the numerical value evaluation model for value index calculation. As shown in Fig.1., the procedure and methodology of this study proposes: (1) the value evaluation process that systemizes the evaluation process of a design; (2) the factors for evaluating the value of the design; (3) a numerical value evaluation model for calculating the value index by indexing the evaluation values; and (4) the conclusion of the study based on the study results, and the future research issues.

2. Value Evaluation Process

As shown in Fig.2., in the proposed value evaluation process, the properties of the target building elements are analyzed to construct factors and to evaluate these. Later, based on the properties of the evaluation factors, the calculated evaluation values are indexed according to the properties of the target factor, via normalization or linear transformation. After the calculation of the value index, the decision-making process is performed, where the optimum design is selected.

3. Evaluation Factors

To resolve the severance of communication among the various parties in a construction project due to their diverse specialties, the differences in the time of their participation in the project, and the difficulty of controlling the inefficient interaction among them, greater emphasis has been placed on the importance of optimizing the three key control elements in a construction project: cost, time, and quality (Gee, 2000). Moreover, as the aim of VE is to reduce the construction cost while maintaining the appropriate quality, it can be said that the VE activities consider cost, time, and quality (Baek & Park, 2003). First, for cost optimization in the design development phase, it is necessary to consider the cost generated in the
construction and maintenance phases. Thus, in this study, the evaluation targets were the construction cost in the construction phase, the repair and replacement cost in the operation and maintenance phase, and the energy cost. Moreover, because the workability (such as the construction difficulty based on the design, the possibility of reducing the construction duration, the smoothness of the construction materials used, and the related system supply), affect the construction duration, in this study the time evaluation targeted the workability. In this study, workability refers to the construction difficulty in relation to the factors affecting the construction duration when developing the design. Finally, while buildings have various functions based on their use, even with the same function, differences still occur in their performances. As it is difficult to ascertain whether buildings with diverse functions also offer good quality, the quality of a building in the design development phase should be evaluated in terms of performance. Therefore, for evaluation, this study targeted the physical performance according to building element, which can be estimated based on the basic design. Fig.3 shows the effect of the design attributes such as the cost, time, and quality, on the initial construction cost, workability, repair and maintenance cost, energy cost, and physical performance, which are the evaluation factors that were selected in this study from the construction and repair and maintenance phases. Fig.4 shows the Composition of Evaluation Factors.

4. Value Evaluation Model

The value evaluation model proposed in this study calculates the value index, first by indexing the evaluation values of the cost, physical performance, and workability, and then by performing a value evaluation.

4.1 Cost Index

Generally, a low cost is evaluated as superior, but as cost is used as a denominator in value evaluation, a low cost evaluation index should result. Thus, in this study, evaluation indexation was performed, first by defining cost as a vector, and then by applying vector normalization, where the direction of the vector was retained while the unit size was converted. The initial construction cost, repair and maintenance cost, and the energy cost of the target design were calculated, and the repair and maintenance cost and energy cost were converted to the present worth (PW) through LCC analysis. The calculated cost of each design was normalized to calculate the cost index (CI) i.e., by dividing the cost of the target design by the norm cost of all the designs. Therefore, the numerical model for calculating CI\(_{jk}\) to \(k\), the cost factor of \(j\), and the design is as follows:

\[
CI_{jk} = \frac{C_{jk}}{\sqrt{\sum_{i=1}^{n} C_{ik}^2}} \quad \text{Eq. (1)}
\]

where

- \(CI_{jk}\): Cost index for factor \(k\) of target design \(j\);
- \(C_{jk}\): Cost for factor \(k\) of target design \(j\);
- \(C_{ik}\): Cost for factor \(k\) of design \(i\);
- \(C\): Cost (the energy cost and repair and maintenance cost, however, are \(PW\));
- \(k\): Cost factor;
- \(j\): Target design; and
- \(i\): Design, \(i=\{1, 2, \ldots, n\}\).

Fig.5 and Table 1 show the concept and an example of CI calculation, respectively. As shown in Table 1, the initial construction cost, repair and maintenance cost, and energy cost of design 1 are $9,598, $3,758, and $46,593, respectively, and those of design 2 are $9,846, $3,512, and $40,247, respectively. If each cost is entered into Eq. (1), the normalized CIs in design 1 will be 0.698, 0.731, and 0.757 while those in design 2 will be 0.716, 0.683, and 0.654.
4.2 Physical Performance Index

The functions of buildings differ based on their use, and the performance required of each element comprising a space also differs from those required of the other elements. Thus, the performance factors required for each target element should be selected, based on which an evaluation should be performed. For the evaluation factors and the methods of evaluating the physical performance of a design, KS F 1010 (KISC, 2005), which involves performance categorization according to building element and which was proposed by the Korea Industry Standard Certificate, was used in this study. KS F 1010 shows the 15 physical performance factors (such as reflection, thermal property, sound insulation, impact sound insulation, and sound absorption) required for the building elements, the corresponding evaluation methods, and the minimum and maximum values of each physical performance factor required for the building elements. Table 2 shows part of the performance categorization according to building element. The scope of the physical performance value of KS F 1010 is wide (between -35 and 61740), and negative and positive numbers coexist. Moreover, in contrast to the other factors, durability of abrasion and impact sound insulation offer better performance when the evaluation value is smaller. Thus, if the evaluation value proposed by KS F 1010 is applied as it is to the calculation of the value index, the value standard will change, resulting in an unreliable evaluation result.

In other words, in calculating the value index according to the value evaluation theory (where the function and performance become numerators to convert the cost-performance ratio to the value), durability of abrasion and impact sound insulation are used as numerators.

If the value in Table 3 is to be used as is, the calculated value index of a design with excellent durability of abrasion and impact sound insulation will be lower than the actual value index. Therefore, as the evaluation value of the durability of abrasion and impact sound insulation reduce, the calculated evaluation index should increase. As such, in this study, linear transformation of linear algebra was applied to express the physical performance factors with evaluation indices. According to the linear-transformation theory, the physical performance index (PI) is calculated by dividing the difference between the physical-performance value of the design and the corresponding physical performance factor required for the building elements. Table 2 shows the integration of the space and element distribution system (HRI, 1998) of an apartment house by Korea Land & Housing Corporation. Some of the factors to be considered in evaluating the physical performance required of the living room floor of an apartment house are the thermal property, impact sound insulation, durability of abrasion, and impact resistance.

For the evaluation of a design, the physical performance evaluation factors are selected based on the properties of the target elements, and the evaluation value is calculated using the test method stipulated in KS F1010. Table 3 shows part of the performance categorization according to building element. The scope of the physical performance value of KS F 1010 is wide (between -35 and 61740), and negative and positive numbers coexist. Moreover, in contrast to the other factors, durability of abrasion and impact sound insulation offer better performance when the evaluation value is smaller. Thus, if the evaluation value proposed by KS F 1010 is applied as it is to the calculation of the value index, the value standard will change, resulting in an unreliable evaluation result.
performance factor $k$ of design $j$ is as follows:

$$PI_{jk} = \frac{PV_{jk} - P_k^{\min}}{P_k^{\max} - P_k^{\min}} \quad \ldots \ldots \ldots \ldots \quad \text{Eq. (2)}$$

where

- $PI_{jk}$: Physical performance index for evaluation factor $k$ of design $j$;
- $P_k^{\max}$: Maximum value of evaluation factor $k$;
- $P_k^{\min}$: Minimum value of evaluation factor $k$;
- $PV_{jk}$: Physical performance value of evaluation factor $k$ of design $j$;
- $P$: Physical performance value;
- $k$: Evaluation index; and
- $j$: Target design.

Fig. 6. and Table 4. show the concept of the physical performance index calculation and an example of such, respectively. As shown in Table 4., if it is assumed that the thermal property and impact sound insulation of design 1 are 1.72 m$^2$K/W and -15 dB, respectively, and that those of design 2 are 1.08 m$^2$K/W and +5 dB, respectively, the linear-transformed thermal index and impact sound insulation index of design 1 from Eq. (2) will be 0.601 and 0.667, respectively, and those of design 2 will be 0.353 and 0.333, respectively.

### 4.3 Workability Index

Workability is a qualitative evaluation factor based on specialists’ construction knowledge and experience. For a reasonable and objective evaluation, the workability evaluation performed by many specialists should be quantified and objectified. Therefore, in this study, the evaluation results were quantified using an interval scale. Moreover, based on group evaluation, the objectified and quantified workability evaluation values were standardized to calculate the workability index. Fig. 7. shows the workability evaluation process.

1. **Workability Evaluation**

First, the workability evaluation factors, as shown in Table 5., are based on the properties of the target building elements. Several specialists evaluate the degree of workability of each of such factors. In a comparison of the alternative and the original plan, if the workability of the proposed alternative is considered to be superior to that of the original plan, "high" is selected; if it is similar or identical to that of the original plan, "same" is selected; and if it is inferior to that of the original plan, "low" is selected. As workability evaluation is based on the original plan, however, the workability of the original plan is always "same" regardless of the factors.

![Fig. 7. Workability Evaluation Process](image)

### Table 4. Calculation of the Physical Performance Index (Example)

| Design 1 | Design 2 |
|----------|----------|
| Physical performance value of KS F1010 | 1.72 | 1.08 |
| $D$ (m$^2$K/W) | -15 | +5 |

Physical performance index

$$P_{D1} = \frac{1.72 - 0.17}{2.75 - 0.17} = 0.601$$

$$P_{D2} = \frac{1.08 - 0.17}{2.75 - 0.17} = 0.353$$

$$P_{E1} = \frac{-15 - 25}{-35 - 25} = 0.667$$

$$P_{E2} = \frac{+5 - 25}{-35 - 25} = 0.333$$

Note: $D$ - Thermal property; $E$ - Impact sound insulation

### Table 5. Checklist and Quantification for Workability Evaluation (Example)

| Evaluation Factor | Design 1 | Design 2 |
|------------------|----------|----------|
| $H$ Smooth supply? | $\checkmark$ | 3 |
| $I$ Can the duration be reduced? | $\checkmark$ | 2 |
| $J$ Safety of work? | $\checkmark$ | 1 |

Note: quantification = high: 3, same: 2, low: 1; evaluation value of the original plan: 2
(3) Calculation of the evaluation value

To objectify the evaluation result from the subjective decision of the evaluators based on their empirical knowledge, all the quantified evaluation values are summed up and divided by the number of participants. Thus, the numerical model for calculating \( EVW_{jk} \) (the evaluation value of the workability (EVW) of design \( j \)) against evaluation factor \( k \) is shown in Eq. (3).

\[
EVW_{jk} = \frac{1}{n} \sum_{a,k=1}^{n} w_{ak} \quad \text{Eq. (3)}
\]

where

- \( EVW_{jk} \): Evaluation value of workability against factor \( k \) of design \( j \);
- \( w \): Quantified value of workability, \( w = \{1, 2, 3\} \);
- \( n \): Number of evaluators, \( n = \{1, 2, \ldots, n\} \);
- \( a \): Evaluator; and
- \( w_{ak} \): Quantified value of evaluator \( a \)'s workability factor \( k \).

Fig. 8 shows the concept of the calculation of the workability evaluation value.

(4) Calculating the workability index

The workability evaluation values calculated above are entered into Eq. (4) to calculate the workability evaluation index. The workability index (WI) of each workability evaluation factor can be calculated by dividing the evaluation value of the design workability by the workability evaluation value norm of all designs. Thus, the numerical model for calculating \( WI_k \), the workability index for \( k \), a workability factor of design \( j \) is as follows:

\[
WI_{jk} = \frac{\sum_{i=1}^{n} EVW_{ij}}{\sqrt{\sum_{i=1}^{n} EVW_{ij}^2}} \quad \text{Eq. (4)}
\]

where

- \( WI_{jk} \): Evaluation index for workability evaluation factor \( k \) of design \( j \);
- \( EVW_{jk} \): Evaluation value of workability evaluation factor \( k \) of target design \( j \);
- \( EVW_{ik} \): Evaluation value of workability evaluation factor \( k \) of design \( i \);
- \( WI \): Workability index;
- \( EVW \): Workability evaluation value;
- \( k \): Workability evaluation factor, \( k = \{1, 2, \ldots, n\} \);
- \( j \): Target design; and
- \( i \): Design, \( i = \{1, 2, \ldots, n\} \).

Table 7 shows an example of the WI calculation. If the evaluation value of the workability of each factor listed in Table 7. is entered into Eq. (7), \( F \), \( G \), and \( H \) of design 1 will be 0.555, 0.707, and 0.625, respectively, and those of design 2 will be 0.832, 0.707, and 0.781, respectively.

Table 7. Calculation of Workability Index (Example)

| Evaluation value of workability | Factor | Design 1 | Design 2 |
|---------------------------------|--------|----------|----------|
| H                               | 2.000  | 3.000    |
| I                               | 2.000  | 2.000    |
| J                               | 2.000  | 2.500    |

(5) Value index

Since a value in VE means the ratio between the cost and performance, the cost index is used as a denominator while the physical performance index and workability index are used as nominators. Therefore, the value index (VI) is calculated by dividing the sum of PI and WI by CI. The numerical model for calculating the VI of design \( j \) is as follows:

\[
WI_{jk} = \frac{\sum_{i=1}^{n} EVW_{ij}}{\sqrt{\sum_{i=1}^{n} EVW_{ij}^2}} \quad \text{Eq. (4)}
\]
where $V_I$: Value index; $CI$: Cost index; $PI$: Physical performance index; $WI$: Workability index; and $j$: Target design.

Table 8. Calculation of the Value Index (Example)

| Evaluation Index | Design 1 | Design 2 | Index change |
|------------------|----------|----------|--------------|
| CI               | A 0.698  | B 0.731  | C 0.757      |
| B                | 0.716    | 0.683    | 0.645        |
| D                | 0.601    | 0.353    | 0.298        |
| PI               | E 0.667  | F 0.555  | G 0.707      |
|                | 0.333    | 0.832    | 0.707        |
| WI               | H 0.625  | 0.781    | 0.156        |
|                  |          | 0.277    |              |
|                  |          | 0.156    |              |

Table 8. Calculation of the Value Index (Example)

| Value Index      | Design 1 | Design 2 | Index change |
|------------------|----------|----------|--------------|
|                  | $V'_I$   | $V_I$    |              |
| Design 1         | $(0.601+0.667+0.555+0.707+0.625)/5=0.698$ | $(0.716+0.683+0.353+0.333+0.707)/5=0.731$ | $0.018$ |
|                  | $0.781$  | 0.716    | -0.018       |
| Design 2         | $(0.333+0.832+0.707+0.781)/4=0.664$ | $(0.716+0.683+0.353+0.333+0.707)/5=0.698$ | $0.021$ |
|                  | $1.443$  | $1.464$  |              |
|                  | $(1.464×1.443)/100=1.55$ | $(1.601+1.443)/100=1.55$ |              |

Note: A - Initial Construction Cost; B - Repair and Maintenance Cost; C - Energy Cost; D - Thermal Insulation; E - Impact Sound Insulation; H - Workability 1; I - Workability 2; J - Workability 3

5. Conclusion

In this study, a value evaluation process for assessing building element designs from the value engineering (VE) of the design development phase was proposed. Initial construction cost, repair and maintenance cost, energy cost, physical performance, and workability were also proposed as design evaluation factors. In addition, to calculate the value index by indexing the evaluation value of each factor, a numerical value evaluation model was proposed. In this study, the cost and workability were indexed via normalization i.e., by dividing the evaluation value of the target design by the evaluation value norm of all designs. Moreover, physical performance, in which various evaluation factors such as impact sound insulation and durability of abrasion coexist, can be indexed by applying the linear-transformation theory of linear algebra i.e., by dividing the difference between the physical performance value of the target design and the minimum performance value of the target physical performance factor by the difference between the maximum and minimum performance values. While the existing value-indexing method using the value matrix and Dell’Isola methods (the two most widely used methods in the field), may be appropriate as the overall evaluation method of the cost and function of the schematic design, it is not appropriate for use in evaluating the life cycle cost and performance of the basic design, where the construction elements of a building are determined. Using the method proposed in this study, however, one can calculate the value index without the need to convert the evaluation values to grades, as is required for the method that is currently being used in the field. In this study, the normalization and linear-transformation methods were used by defining the evaluation value as a vector. In such methods, however, a complex calculation procedure needs to be used. To address this issue, further research is necessary not only to reduce the time required for the evaluation but also to integrate the proposed method with the existing VE programs. However, despite the fact that construction projects often have a long duration and that some buildings have a long lifecycle, in this study, the corresponding sensitivity was not considered. Therefore, further research should be conducted to develop a model which to analyze the cost change based on the simultaneous price fluctuation.

Acknowledgement

The present research was conducted by the research fund of Dankook university in 2011.

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