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Research Article

Analysis Model of Cost-Effectiveness for Value Evaluation of Building Elements

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As various building materials have been developed, the combination of materials that make up the building elements has also increased exponentially. The materials making up the elements of the building will affect the performance of the building and the LCC. In order to improve the value of buildings in Korea, value engineering has been mandated in public construction projects with a project cost of over 10 billion won since 2000. The value index for systems (materials, elements, facilities, etc.) constituting buildings is calculated. However, the method for calculating the value index has not yet been normalized. The performance evaluation of the building systems (materials, elements, facilities, etc.) used in the current work and the method of calculating the value index for converting the LCC into a grade may vary depending on how the range of the grade is set. Even if the objects being evaluated are the same, there arises a problem that the results change depending on the value evaluation method. Therefore, this study tried to develop a value evaluation method that could draw consistent value evaluation results. For this purpose, this study presents a cost-effectiveness analysis model for the physical performance of the building elements and the value evaluation of LCC. Since the various physical performances of the building elements have different properties, normalization is required for comparison of physical performance values. In order to normalize the LCC and the 14 different physical performances of the building elements, a numerical model was designed using a linear transformation method and a vector normalization method. The cost-effectiveness analysis model proposed in this study was applied to two types of floor elements applicable to apartments in Korea, in order to evaluate the value and verify the consistency of this study's model. The cost-effectiveness analysis model proposed in this study can help to derive reliable results when it comes to value evaluation for various existing building element compositions.

1. Introduction

1.1. Background. Research and development on new materials and new methods are actively carried out in all areas including structure, materials, and design. The size of buildings is increasing and buildings are becoming more complicated. The kinds of materials that make up buildings are also becoming more diverse. The materials and construction methods used for the building affect the quality of the building. This also means the proportion of building materials and costs have increased. Building materials have a great influence on the life cycle cost (LCC) of the building [1]. However, material selection depends on limited information provided by the manufacturer and on construction cost. Life cycle costs, one of the characteristics of materials, are not considered [2]. Korea introduced value engineering (hereinafter, VE) in 2000 to improve building value and competitiveness of the construction industry. As a result, LCC review and design review were obligatory for public buildings costing 10 billion won or more. However, due to a misconception by construction workers, who consider VE a simple cost reduction method, VE is being used as a cost-saving method rather than improving the value of buildings [3–5]. The Korean government requires the "value index" to be entered into the VE proposal when presenting alternatives through VE. However, no specific method for calculating the value index has been proposed [6]. As a result, Korean companies specializing in VE use different value evaluation methods. According to the value evaluation method, the evaluation results are different even when the evaluation object is the same, which is problematic. It is difficult to guarantee reliability of the evaluation results. Therefore, in order to improve the value of buildings efficiently and effectively through VE, it is necessary to develop a value evaluation method that can produce objective and consistent results.

1.2. Literature Review and Purpose. Previous studies related to the selection of building materials have been carried out from different perspectives. Alibaba and Özdeniz analyzed the importance of the expected performance and requirements of the building elements and proposed a material selection method that reflects the analysis results [7]. Zavadskas et al. have argued for the necessity of complex decision-making considering various requirements for material selection [8]. Jee and Kang developed a material selection system by combining entropy method and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) concepts [9]. Previous studies related to the cost of building materials have been performed mainly on specific materials. As a representative study, Rahman et al. developed a system for selecting the optimal roof material in terms of cost [10]. Perera and Fernando proposed a model for selecting roof materials which focused on the persisting period [11]. Do et al. proposed a method for selecting material using analytic hierarchy process [12]. In recent years, interest in ecofriendliness has increased, affecting material selection studies. Castro-Lacouture et al. proposed a model for selecting the best environmentally friendly materials within a given budget [13]. Yang and Ogunkah conducted research to select ecofriendly materials meeting various requirements [14]. Thus, previous studies on material selection have been actively conducted mainly on the physical properties, cost, and environmental impact of materials. According to previous studies, it was confirmed that the running cost after construction of a building is larger than the initial cost [15]. The importance of LCC analysis is emphasized in the planning of construction projects. However, previous studies have focused on the performance of materials and construction cost, which is limited to initial cost. When selecting building materials, considering the running cost in the maintenance phase is insufficient. Previous studies for optimizing the value of building materials mainly use Value Matrix [16] and Dell'Isola's Method [17] of Caltrans (California Department of Transportation), which is a method of calculating the VE value index. The Value Matrix is a method of measuring functional value using the cost and the performance of the designs. The Value Matrix converts the performance of each design into a grade. The result is multiplied by the weight according to the priority of each performance factor, then it is converted into the performance contribution, and then the total performance value is calculated by summing up the performance contribution. After this, the total performance value is divided by the total cost in order to calculate the value index. The optimum design is then selected according to the value enhancement rate. Dell'Isola's Method, on the other hand, calculates weights based on the importance of each cost and the importance of each item and then converts the cost and performance evaluation values into a grade. After that, the best score is selected by using the total score, which is the sum of the weight of the evaluation item and the grade of each design item. In this respect, it is advantageous to convert the evaluation values used in the Value Matrix and Dell'Isola's Method into a grade. However, both methods are not expected to provide objective results because the evaluation results may vary depending on how the grade scale is set. In addition, among the items for evaluation the value of building materials, there are superior items with higher numerical values. On the other hand, there are superior items with lower numerical values. Therefore, in order to evaluate the value of building materials and obtain reliable results, it is necessary to utilize the properties (cost and performance) of building materials. Recently, various kinds of building materials have been developed and the combinations of groups of materials that constitute building elements have increased exponentially. In addition, the importance of the composition of the elements, which is a combination of building materials, has also been emphasized. This study aims to support value-based decision-making by presenting a numerical model that evaluates value through evaluating the performance of building elements and LCC analysis.

2. Evaluation Factors and Procedures

The value engineering method represents the performance of the material and LCC as a value. The building is composed of several spaces, and the space is made up of a combination of various elements such as the inner wall, outer wall, and floor. The performance and cost of a building can be divided into the performance and cost of each element. And the optimum design of the building can be achieved through the integration of the optimal design for each element [18]. Thus, building element optimization can be achieved through a combination of materials with optimal value. The optimization of the building elements through a combination of materials can be expressed by the following characteristic matrix (see the following formula):

$$E = \begin{array}{c} \\ M_1 \\ \cdot \\ M_i \\ \cdot \\ M_m \end{array} \begin{array}{c} \begin{array}{ccccc} X_1 & \cdots & X_j & \cdots & X_n \end{array} \\ \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \cdot & & \cdot & & \cdot \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdot & & \cdot & & \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array}. \quad (1)$$

In this, E is the building element, $M_1 \cdots M_m$ are the materials constituting the building elements, $X_1 \cdots X_n$ are the performance or cost of the materials, and X_{ij} is the performance or cost j of M_i that is arbitrary material.

2.1. Evaluation Factor 1: Physical Performance. The function of buildings, due to technological development, has diversified. In VE (which is aimed at improving the value of a building), the value is evaluated by analyzing the functions of the elements constituting the building such as materials, elements, and systems. However, even in buildings with the same function, there is a difference in performance. Buildings with various functions cannot be regarded as superior in performance. Therefore, the value of buildings should be evaluated in terms of performance. The characteristics of

Table 1: Physical performance by element required for building space.

Code	Item	①			②			③			④			⑤			⑥			⑦
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	C
P01	Reflectivity	*		*	*		*	*		*	*		*	*		*	*		*	
P02	Insulation	*		*	*		*	*		*	*			*			*			*
P03	Sound insulation	*	*		*	*		*	*		*	*		*	*		*	*		
P04	Impact sound insulation			*			*			*										
P05	Sound absorption		*			*			*						*			*		
P06	Waterproofing	*			*			*			*	*	*	*		*	*		*	*
P07	Damp-proofing	*		*	*		*	*		*	*		*	*		*	*		*	
P08	Air tightness	*	*		*	*		*	*		*	*		*	*		*	*		
P09	Inner pressure			*			*			*			*			*			*	*
P10	Impact resistance	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
P11	Compressibility resistance			*			*			*						*			*	*
P12	Wear resistance			*			*			*			*			*			*	*
P13	Fire resistance	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
P14	durability	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Note. Asterisk: required performance by element of building space; ①: living room; ②: bedroom; ③: kitchen; ④: bathroom; ⑤: hall; ⑥: stairs; ⑦: roof; A: outer wall; B: inner wall; C: floor.

performance are divided into evaluation of unit material and element evaluation, which is a combination of materials. For example, the abrasion resistance of the floor of an apartment living room should be evaluated for floor finishes, while the impact sound insulation should be evaluated for the entire floor area.

2.2. Evaluation Factor 2: LCC. In order to optimize the overall cost of a building, it is necessary to consider the costs incurred in the construction and maintenance phases [19]. The maintenance of the building generally refers to activities such as preliminary inspection, repair, and replacement to restore the function or performance in order to restore the damaged part and to provide convenience and safety to the user after the buildings completion. Figure 1 shows the repair and replacement cycle over time and the performance level of the building. Assuming that the performance level is 100% immediately after the completion of the building, the performance of the building gradually deteriorates due to various factors such as climate and physical environment. If a certain level of performance degradation occurs, repair or replacement should be implemented. These activities are repeated until the life of the building is completed [20]. Therefore, the cost of the elements and materials constituting the building should be analyzed for the initial cost and the running cost.

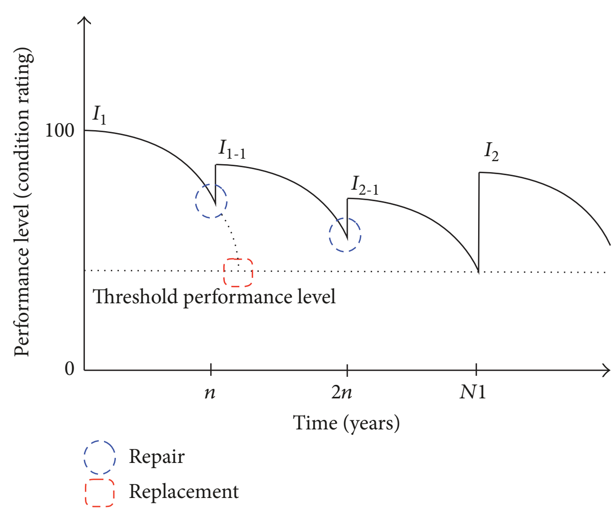


Figure 1: Performance level of the building.

2.3. Evaluation Process. As shown in Figure 2, this study model evaluates the physical performance and LCC of building elements. It evaluates the value using the physical performance and the cost-effectiveness of LCC.

3. Evaluation Model

3.1. Physical Performance Evaluation and Normalization. The building offers the functionality and performance that users want through a combination of various materials and systems. Figure 3 shows the structure of the building. In order to realize the optimal performance of the human activity space, it is necessary to secure the performance of the elements constituting the space and the materials constituting the elements.

In order to define the performance of the materials, the composition of system of elements and spaces (which are the higher layers) should also be defined. Table 1 shows the 14 performance items related to the building elements defined based on the Korean building performance standard KS F ISO 6241 [21]. The living room, the bedroom, the kitchen, the bathroom, the hall, the stairs, and the roof in Table 1 are the main spaces of the building corresponding to Room Class in Figure 3. The outer wall, the inner wall, and the floor are the elements corresponding to the Element

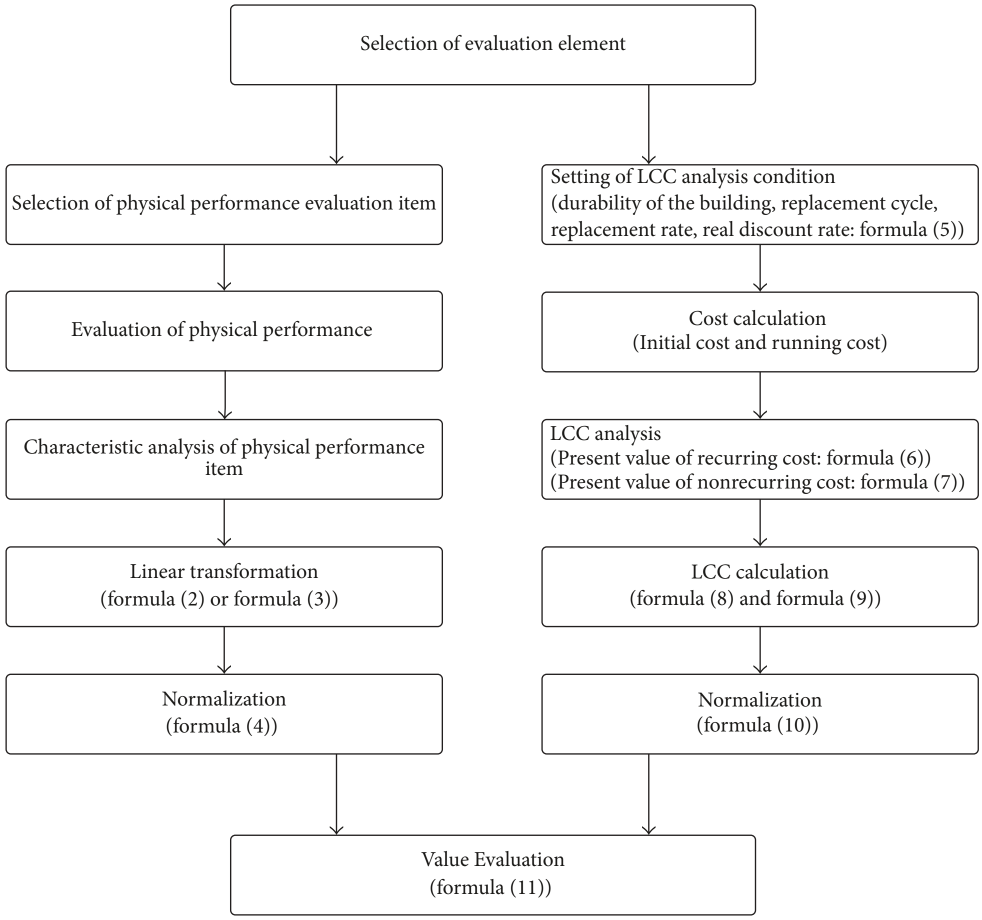


Figure 2: Procedure.

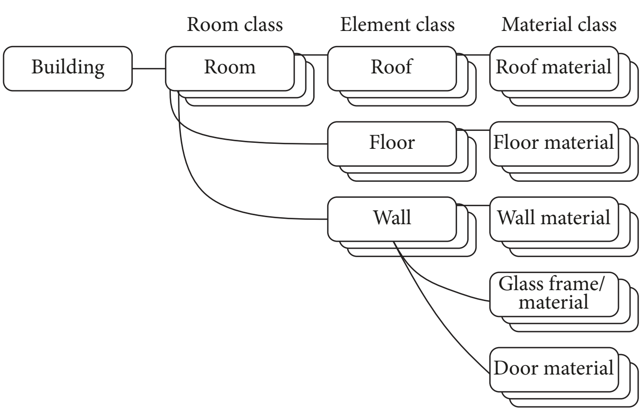


Figure 3: Hierarchy of building components.

Class. As an example, the kitchen with an outside wall is composed of an inner wall, an outer wall and a floor. The performance associated with the inner wall of the kitchen is sound insulation, sound absorption, air tightness, and impact resistance. The performance associated with the outer wall of the kitchen is reflectivity, insulation, sound insulation, waterproofing, damp-proofing, and air tightness. The performance associated with the floor of the kitchen is reflectivity, insulation, impact sound insulation, damp-proofing, and inner pressure. It is possible to select the items required for the evaluation among the defined physical performance items and to define the required performance per element. The physical performance value is calculated using the test report conducted by the test method (KS F 2257–1, KS F 2257–4, KS F 2257–5, KS F 2257–6, KS F 2257–7, KS F 2271, and KS F 2273) suggested in the Korean Industrial Standard. The performance standard KS F 1010 of the building element of Table 2 is notified by the Korean Agency for Technology and Standards of the Ministry of Knowledge Economy.

The physical performance of Table 2 is composed of superior items as the numerical value is larger and improved items as the numerical value decreases. For example, the minimum performance value of reflectivity is +7 and the maximum performance value is +56. The smaller the number, the better. Conversely, the impact sound insulation has a minimum performance value of +25 and a maximum performance value of −35. The lower the number, the better. Wear resistance has a minimum performance value of +3.2 and a maximum performance value of +0.1. The lower the number, the better. Thus, the various types of physical performance values have different sizes. Therefore, normalization is required to compare physical performance values [9].

In order to compare the physical performance values on the same scale, it is necessary to normalize all attribute

Table 2: Performance criteria and scope of building elements.

Code	Item	Measurement method	Unit	Min (inferiority)			◂ Grade ▸			Max (superior)
P01	Reflectivity	Light reflectance	(%)	7	10	14	20	28	40	56
P02	Insulation	Heat Flow Resistance	m^2K/W	0.17	0.26	0.43	0.67	1.08	1.72	2.75
P03	Sound insulation	Transmission Loss	dB	12	20	28	36	44	52	60
P04	Impact sound insulation	Difference in sound Pressure level on the standard curve	dB	25	15	5	−5	−15	−25	−35
P05	Sound absorption	Sound absorption rate	(%)	20	30	40	50	60	70	80
P06	Waterproofing	Watertight pressure	Pa	98.0	156.8	245.0	392.0	617.4	980.0	1568.0
P07	Damp-proofing	Moisture resistance	$m^2{\cdot}d{\cdot}mmAq/g$	0.1	1	10	100	250	630	1000
P08	Air tightness	Airtight resistance	$m^2{\cdot}\ h/m^3$	0.015	0.06	0.25	1.0	4.0	15	60
P09	Inner pressure	Unit load	N/m^2	392.0	695.8	1225	2254	3920	9996	12250
P10	Impact resistance	Safety shock energy	N·cm	441	617.4	1568	3920	9996	24500	61740
P11	Compressibility resistance	Local compression load	N/cm^2	127.4	294	784	1960	4900	12250	29400
P12	Wear resistance	Wear amount	mm	3.2	1.8	1.0	0.56	0.32	0.18	0.1
P13	Fire resistance	Heating time	min	5	10	15	30	60	120	180
P14	Durability	Persisting period	Year	5	8	12	20	32	50	80

values to values between 0 and 1. Normalization techniques that convert physical performance values with different measurement units into comparable measures include (1) a normalization technique using an average value of physical performance values, (2) a normalization technique using an intermediate value of physical performance values, (3) a vector normalization technique that divides the value by the Norm of the physical performance item, and (4) a linear transformation technique that divides the maximum value of each physical performance value by the remaining physical performance value. The normalization method using the first average value assumes that the average value of the data is 0 and the normalization method using the second intermediate value assumes that the intermediate value of the data is 0. The normalization method using an average value and the normalization method using an intermediate value set an average value or an intermediate value as a reference (0) and place the other values to the left and right. Therefore, the normalization technique using an average value and the normalization technique using an intermediate value are not suitable for integrating multiple physical performance values because they have negative values when the normalization value is smaller than a reference value of 0. In the third vector normalization technique, the Norm of the vector is set to 1, and the ratio of each vector is calculated. Therefore, smaller values are not suitable for normalizing the physical performance of a building site that contains superior items such as impact sound insulation. The fourth linear transformation technique is appropriate method for the coexistence of superior items with higher numerical values and of lower numerical values. It is also possible to rearrange different physical performance values with different preferences and convert them to the same preference. However, the impact sound insulation including negative value (−) in the physical performance items of the building elements cannot expect a correct result when using the general linear transformation model [22]. This study has designed a numerical model that can normalize the physical performance values of the building elements containing negative value (−) by using the linear transformation technique among the four normalization methods. The physical performance values of the building elements in Table 2 are normalized to values between 0 and 1 as shown in Table 3.

As the numerical value increases, a perfectly scored item can be normalized by dividing the absolute value that subtracts performance value from minimum performance value by the value obtained by subtracting the minimum performance value from the maximum performance value as shown in formula (2). In addition, as the numerical value becomes lower, a perfectly scored item can be normalized by dividing the value that subtracts the absolute value of performance value from minimum performance values by the absolute value obtained by subtracting the minimum performance value from the maximum performance value as shown in formula (3). In the evaluation of a plurality of performances, each normalized physical performance value is summed by using formula (4) and arithmetic averaging is performed to calculate a normalized physical performance value of the corresponding region.

$$\mathrm{EP}_{\mathrm{Linear\_}i(\mathrm{Type\_1})} = \frac{\left(\mathrm{EP}_i^{\min} - \mathrm{EP}_i\right)}{\left(\mathrm{EP}_i^{\max} - \mathrm{EP}_i^{\min}\right)} \tag{2}$$

Table 3: Normalization of physical performance values of the building elements.

Code	Item	Min (inferiority)	◂ Grade ▸					Max (superior)
P01	Reflectivity	0.000	0.061	0.143	0.265	0.429	0.634	1.000
P02	Insulation	0.000	0.035	0.101	0.194	0.353	0.601	1.000
P03	Sound insulation	0.000	0.167	0.333	0.500	0.667	0.833	1.000
P04	Impact sound insulation	0.000	0.167	0.333	0.500	0.667	0.833	1.000
P05	Sound absorption	0.000	0.167	0.333	0.500	0.667	0.833	1.000
P06	Waterproofing	0.000	0.040	0.101	0.201	0.356	0.603	1.000
P07	Damp-proofing	0.000	0.001	0.010	0.100	0.250	0.630	1.000
P08	Air tightness	0.000	0.001	0.004	0.016	0.067	0.250	1.000
P09	Inner pressure	0.000	0.026	0.070	0.157	0.298	0.554	1.000
P10	Impact resistance	0.000	0.003	0.018	0.057	0.156	0.393	1.000
P11	Compressibility resistance	0.000	0.006	0.022	0.063	0.163	0.414	1.000
P12	Wear resistance	0.000	0.452	0.710	0.852	0.929	0.974	1.000
P13	Fire resistance	0.000	0.029	0.057	0.143	0.314	0.657	1.000
P14	Durability	0.000	0.040	0.093	0.200	0.360	0.600	1.000

$$\mathrm{EP}_{\mathrm{Linear}\_i(\mathrm{Type}\_2)} = \frac{\left(\mathrm{EP}_i^{\min} - \left|\mathrm{EP}_i\right|\right)}{\left(\left|\mathrm{EP}_i^{\max} - \mathrm{EP}_i^{\min}\right|\right)} \quad (3)$$

$$\mathrm{EP}_{\mathrm{Normalization}} = \frac{\sum_{i=1}^{n} \mathrm{EP}_{\mathrm{Linear}\_i}}{n}, \quad (4)$$

where $\mathrm{EP}_{\mathrm{Normalization}}$ is the normalized physical performance value of the evaluated element, $\mathrm{EP}_{\mathrm{Linear}\_i}$ is the linearly converted physical performance value, $\mathrm{EP}_i^{\max}$ is the maximum performance value of the physical performance item, $\mathrm{EP}_i^{\min}$ is the minimum performance value of the physical performance item, EP_i is the physical performance value of the evaluated element, and i is the physical performance item of the evaluated element.

3.2. LCC Analysis and Normalization. The cost of materials consists of the initial cost and the running cost and it analyzes LCC. In this study, the initial cost is the construction cost and the construction stage is set as the present point in the LCC analysis. Therefore, the construction cost itself becomes the present value. The running cost is the future cost of maintenance in the process of using the building after completing construction. It is divided into the cost that is repeated every year (Recurring cost) and costs which are not required to be repeated every year but at a certain time (Nonrecurring cost). The running cost is equivalent to the construction cost at the same point in time when using the present value method. At this time, in order to convert future costs to present value, it is necessary to consider the change in value of money with time. The discount rate is the rate of change in the cost value over time. In this study, we use the real discount rate as given by the price fluctuation effect. The real discount rate is calculated using the nominal discount rate and the inflation rate as shown in formula (5). Recurring cost is converted into present value using formula (6) and nonrecurring cost is converted into present value using formula (7).

$$i_r = \left\{\frac{(1+i_n)}{(1+f)}\right\} - 1 \quad (5)$$

$$\mathrm{RPV} = \frac{\left\{(1+i_r)^m - 1\right\}}{\left\{i \times (1+i_r)^m\right\}} \times \mathrm{RC} \quad (6)$$

$$\mathrm{NPV} = \left\{\frac{1}{(1+i_r)^n}\right\} \times \mathrm{NC}, \quad (7)$$

where RPV is the present value of the recurring cost, NPV is the present value of the nonrecurring cost, RC is the recurring cost, NC is the nonrecurring cost, m is the period of occurrence of recurring cost, n is the time of occurrence of nonrecurring cost, i_r is the real discount rate, i_n is the nominal discount rate, and f is the inflation rate.

The LCC of the material constituting the evaluation element can be calculated by substituting construction cost, RPV, and NPV of the previously calculated materials into formula (8). The LCC of the element is calculated by summing up the LCC of each material as shown in formula (9).

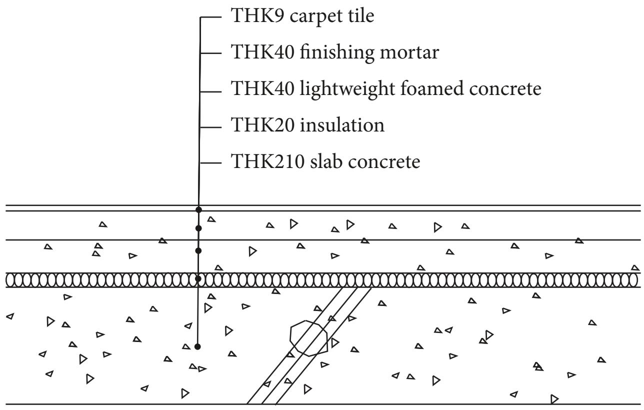
$$\mathrm{MLCC} = \sum_{i=1}^{n} \left(\mathrm{CC}_i + \mathrm{RPV}_i + \mathrm{NPV}_i\right) \quad (8)$$

$$\mathrm{ELCC} = \sum_{i=1}^{n} \mathrm{MLCC}_i, \quad (9)$$

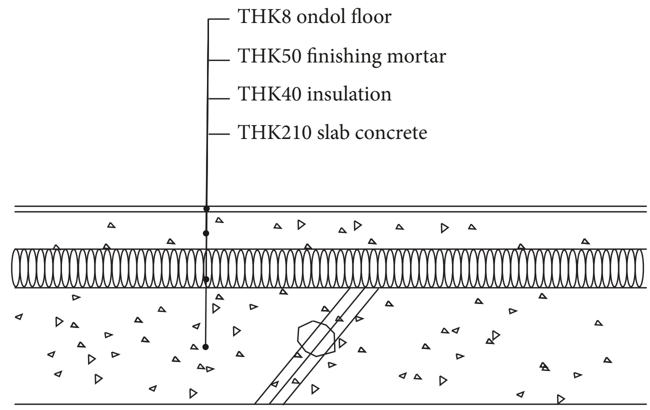
where ELCC is the LCC of the evaluation element, MLCC is the LCC of the evaluation material, CC is the construction cost, RPV is the present value of the recurring cost, NPV is the present value of the nonrecurring cost, and i is the evaluation material.

Generally, in the cost planning of a building, the lower the cost, the better, and the higher the cost, the less desirable. That is, the cost and the economy are inversely related. However, in this study, the LCC is used as a denominator to evaluate the cost-effectiveness of materials or elements. Therefore, the LCC and the normalized LCC are proportional.

Previously, the physical performance of the building elements was normalized using a linear transformation technique (formula (2) and formula (3)). In order to use LCC as a denominator, the LCC should be normalized between



(a) Type 1



(b) Type 2

Figure 4: Case study subject.

0 and 1 and the physical performance because the linear transformation value of the physical performance is used as the numerator when evaluating the value using formula (11). Among the four normalization techniques described above, the normalization method using an average value and the normalization method using an intermediate value are not suitable for the normalization of the LCC because they have a negative value when the normalization value is smaller than a reference value of zero. In addition, the LCC cannot use the linear transformation technique for normalization because only the maximum value and the minimum value exist when there are less than two cost-effectiveness analysis objects. On the other hand, the vector normalization method can be utilized as a method of normalizing the LCC since the Norm of the vector is set to 1 and the ratio of each vector is calculated. Here, the best performance value is normalized to 1 using formulas (2) and (3). In order to calculate the value index through value evaluation, the normalized physical performance value and the normalized LCC should be made to the same scale. In other words, the maximum value of the LCC of proposed building element components should be 1. In this study, a numerical model is designed to normalize LCC of a number of building element components using a vector normalization technique. The maximum value of the LCC is normalized to 1. LCCs other than the maximum value are normalized to a value ranging from 0 to less than 1.

The normalized LCC can be calculated by dividing the LCC to be evaluated by the maximum value of the LCCs of the applicable material or constituent elements as follows:

$$\mathrm{ELCC}_{\mathrm{Normalization}} = \frac{\mathrm{ELCC}_i}{\mathrm{ELCC}^{\mathrm{Max}}}, \tag{10}$$

where $\mathrm{ELCC}_{\mathrm{Normalization}}$ is the normalized LCC of the element to be analyzed, $\mathrm{ELCC}^{\mathrm{Max}}$ is the maximum value of the LCC of the element to be analyzed, ELCC_i is the LCC of the element to be analyzed, and i is the element to be analyzed.

3.3. Value Evaluation. In this study, value means the ratio of the physical performance of materials and elements to the LCC, for example, cost-effectiveness. Therefore, the larger the value, the better. The value is evaluated using the normalized physical performance value and the normalized LCC as calculated above. The value is calculated by dividing the normalized physical performance value of the evaluated element by the normalized LCC using

$$\mathrm{EV}_i = \frac{\mathrm{EP}_{\mathrm{Normalization}\_i}}{\mathrm{ELCC}_{\mathrm{Normalization}\_i}}, \tag{11}$$

where EV_i is the value of the evaluated element, $\mathrm{ELCC}_{\mathrm{Normalization}\_i}$ is the normalized LCC of the evaluated element, and $\mathrm{EP}_{\mathrm{Normalization}\_i}$ is the normalized physical performance value of the evaluated element.

4. Case Study

4.1. Selection of Evaluation Elements and Evaluation Items. The consistency of the building element value evaluation model proposed in this study was tested by using two types of base floor element components that can be used in Korean apartment housing, as shown in Figure 4. Type 1 is made up of slab concrete (THK210), interstory noise protection, cushioning for insulation (THK20), lightweight foamed concrete (THK40), mortar (THK40), and carpet tiles (THK9) for finishing. Type 2 is made up of slab concrete (THK210), interstory noise protection, cushioning for insulation (THK40), mortar (THK50), and ondol floor (THK8) for finishing.

Among the required performances for living room floor elements in the apartment, the physical performance evaluation of the case selected insulation and impact sound insulation, which satisfies the performance standard according to the Korean Building Act. LCC selected the construction cost of the floor element and the repair replacement cost of the floor finish as evaluation items.

Table 4: Insulation property output data.

Element Plan	Material	Thickness (mm)	Heat conduction rate (W/mK)	Heat flow resistance (m^2K/W)
Type 1	Resistance of internal heat transfer	-	-	0.086
	Carpet tiles	9	0.059	0.153
	Ondol floor	-		
	Cement mortar	40	1.4	0.029
	Lightweight foamed concrete	40	0.16	0.250
	Cushioning for insulation	20	0.033	0.606
	Concrete slab	210	1.6	0.131
	Internal transfer resistances	-	-	0.086
	Total			1.341
Type 2	Internal transfer resistances	-	-	0.086
	Ondol floor	8	0.10	0.080
	Cement mortar	50	1.4	0.036
	Cushioning for insulation	40	0.033	1.212
	Concrete slab	210	1.6	0.131
	Internal transfer Resistances	-	-	0.086
	Total			1.631

Table 5: Physical performance evaluation result.

Performance	Item	
	Type 1	Type 2
Physical performance value before normalization		
Insulation (m^2K/W)	1.341	1.631
Impact sound insulation (dB)	−4.500	−2.500
Normalized physical performance values		
Insulation	$\frac{\lvert 0.17-1.341\rvert}{(2.75-0.17)}=0.454$	$\frac{\lvert 0.17-1.631\rvert}{(2.75-0.17)}=0.566$
Impact sound insulation	$\frac{(25+\lvert -4.5\rvert)}{\lvert -35-25\rvert}=0.492$	$\frac{(25+\lvert -2.5\rvert)}{\lvert -35-25\rvert}=0.458$
Physical performance	$\frac{(0.454+0.492)}{2}=0.473$	$\frac{(0.566+0.458)}{2}=0.512$

4.2. Evaluation and Normalization

4.2.1. Physical Performance

(1) Evaluation and Character Analysis. The insulation is calculated by the thermal resistance calculation method using the thickness and the thermal conductivity of the material constituting the floor element. Since the impact sound insulation is an item which cannot be evaluated by the floor element composition drawing, the test result of the official agency is used. The total heat transfer rate of concrete slab, floor cushioning material, lightweight foamed concrete, cement mortar, and carpet tiles, which constitute Type 1, is 3.252 W/m^2K, as shown in Table 4. The heat flow resistance of the floor element is 1.341 m^2K/W, taking into account the upper and lower internal transfer resistance. The impact sound blocking property calculated by using the sound pressure level difference on the standard curve of a heavy impact sound and a light impact sound is −4.5 dB. The heat flow resistance and impact sound blocking property of Type 2 evaluated using the same method as Type 1 are 1.631 m^2K/W and −2.5 dB. Therefore, the impact sound blocking property was excellent in Type 1 and the insulation property was excellent in Type 2.

(2) Linear Transformation and Normalization. The larger the numerical value, the better the insulation so it is normalized by using formula (2). However, the impact sound insulation is better as the numerical value is smaller so it is normalized by using formula (3). The insulation performance 1.341 m^2K/W and impact sound insulation performance −4.5 dB in Type 1 were normalized to 0.454 and 0.490, as shown in Table 5. The normalized physical performance calculated by substituting in formula (4) is 0.473. Also, the insulation performance 1,631 m^2K/W and impact sound insulation performance −2.5 dB in Type 2 were normalized to 0.566 and 0.458. The normalized physical performance calculated by substituting in formula (4) is 0.512. Therefore, the integrated physical performance that comprehensively evaluated both the physical performances of insulation and impact sound insulation is 0.473 for Type 1 and 0.512 for Type 2, which means Type 2 was evaluated as superior in terms of physical performance.

Table 6: Initial cost calculation data.

Item	Material	Unit	Standard	Cost (Won, ₩)
Type 1	Carpet tiles	m^2	THK9	13,300
	Cement mortar	m^3	THK40	52,773
	Lightweight foamed concrete	m^3	THK40	11,160
	Floor cushioning material	m^2	THK20	3,512
	Concrete slab	m^3	THK210	11,929
	Total			92,674
Type 2	Ondol floor	m^2	THK8	15,758
	Cement mortar	m^3	THK50	65,967
	Floor cushioning material	m^3	THK40	5,130
	Concrete slab	m^3	THK210	11,929
	Total			98,784

4.2.2. LCC

(1) Setting Analysis Conditions. The duration of the building was set at 40 years in order to calculate Type 1 and Type 2 LCCs. The actual discount rate to convert the replacement cost of the flooring finishing material, which is a future cost, to the present value is based on Korea's nominal discount rate of 3.51% in 2017 and the inflation rate of 0.8%. As a result, substituting into formula (5), the real discount rate of 2.7% was applied as shown in

$$i_r = \left\{ \frac{(1 + 0.0351)}{(1 + 0.008)} \right\} - 1 = 0.027. \tag{12}$$

(2) Cost Calculation

Initial Cost. Construction costs of Type 1 and Type 2 were calculated as cost per unit by using the standard price and the unit price of the standard construction market in 2017, which was compiled by the Ministry of Land, Infrastructure and Transport, Korea's leading construction industry. The calculated construction costs are ₩92,674 for Type 1 and ₩98,784 for Type 2, as shown in Table 6.

Running Cost. According to Korea's facility management standards, the life cycle of carpet tiles, the finishing material of Type 1, is set to be replaced 15% every 10 years and 100% every 20 years. The life cycle of ondol floor, the finishing material of Type 2, is set to be replaced 15% every 7 years and 100% every 25 years. The LCC of the replacement cost due to the aging of the carpet tiles and the ondol floor during the life cycle of 40 years of case building was analyzed as 6 times in Type 1 and LCC was analyzed as ₩10,232 as shown in Table 7. Type 2 required a total of 6 replacements and LCC was analyzed as ₩14,945.

The initial cost of construction costs is the current cost, so it is regarded as the present value. When the initial cost and the running cost are combined, the LCC of Type 1 is ₩102,906 and the LCC of Type 2 is ₩113,729. Therefore, Type 1 was analyzed to be superior in terms of LCC.

(3) Normalization. The previously calculated LCCs of Type 1 and Type 2 were normalized by substituting in formula (10). As shown in Table 8, Type 1 was calculated as 0.905 and Type 2 was calculated with a maximum value of 1.000.

4.2.3. Value Evaluation. The normalized physical performance value and the normalized LCC of Type 1 and Type 2 were substituted into formula (11) to calculate the value. Table 9 shows the evaluation process. Type 1 is 0.522 and Type 2 is 0.512.

5. Conclusion

This study presents a numerical model for selecting value, oriented building element components by evaluating building elements composed of various materials in terms of performance and LCC.

The main contents are as follows.

(1) The physical performance, construction cost, and maintenance cost of constituent materials and elements are presented as items for evaluation. (2) Physical performance is normalized to a comparable form by presenting a numerical model (formula (2), formula (3), and formula (4)) using a linear transformation method. (3) LCC is normalized to a comparable form by presenting a numerical model (formula (10)) using a vector normalization method. (4) Value evaluation method (formula (11)) of VE was applied to evaluate the physical performance value and the cost-effectiveness of LCC. (5) In order to verify the consistency of cost-effectiveness analysis, the physical performance and the LCC for the two types of floor element used in Korean apartment housing were assigned to the formula. The results are as follows.

The insulation of Type 1 was 1.321 m^2K/W and the impact sound insulation was −4.5 dB normalized to 0.454 and 0.492. The insulation of Type 2 was 1.631 m^2K/W and the impact sound insulation was −2.5 dB normalized to 0.566 and 0.458. The LCC of Type 1 was ₩102,906 normalized to 0.905. The LCC of Type 2 was ₩113,728 normalized to 1.000. The values of the analytical floors calculated using the normalized physical performance and the normalized LCC are 0.522 and 0.512, respectively.

Table 7: Running cost calculation data.

Item	Repair replacement cycle (Year)	Repair replacement rate (%)	LCC (Won, ₩)
Type 1	10	15	$13{,}300 \times \left\{ \frac{1}{(1+0.027)^{10}} \right\} \times 0.15 = 1{,}528$
	20	100	$13{,}300 \times \left\{ \frac{1}{(1+0.027)^{20}} \right\} \times 0.15 = 7{,}806$
	30	15	$13{,}300 \times \left\{ \frac{1}{(1+0.027)^{30}} \right\} \times 0.15 = 897$
	Total		10,232
Type 2	7	15	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{7}} \right\} \times 0.15 = 1{,}691$
	14	15	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{14}} \right\} \times 0.15 = 1{,}627$
	21	15	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{21}} \right\} \times 0.15 = 1{,}351$
	25	100	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{25}} \right\} \times 1.0 = 8{,}093$
	32	15	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{32}} \right\} \times 0.15 = 1{,}007$
	36	15	$15{,}754 \times \left\{ \frac{1}{(1+0.027)^{36}} \right\} \times 0.15 = 906$
	Total		14,945

Table 8: LCC analysis result.

Item	LCC
Type 1	$\text{LCC}_{\text{Normalization\_1}} = \frac{102{,}906}{113{,}729} = 0.905$
Type 2	$\text{LCC}_{\text{Normalization\_2}} = \frac{113{,}729}{113{,}729} = 1.000$

Table 9: Value evaluation data.

Item	Value
Type 1	$V_1 = \frac{0.473}{0.905} = 0.522$
Type 2	$V_1 = \frac{0.512}{1.000} = 0.512$

Previous studies suggesting optimal building materials and building element selection methods have been used to convert performance and cost to a grade. However, there is a problem that the evaluation results are different depending on the set grade range of the preceding methods. This study is different from the previous study methods in that the physical performance of the building elements and the LCC are converted to numbers between 0 and 1 using the linear transformation method and the vector normalization method.

Recently, various kinds of building materials are being developed. Therefore, the combination group of materials that can form the building elements is increasing exponentially. As a result, the importance of the composition of the element, which is a combination of building materials, has been emphasized and a lot of time and effort are required to make a decision for selecting the optimum element composition. This study's model does not go through the complex process of converting the performance and cost into a grade and assigning the grade that was used in the existing methods. Since the value index is calculated by substituting the physical performance value and the LCC into the proposed cost-effectiveness analysis model, the time required to make the optimal choice of the building elements composed of various materials can be reduced. In addition, this study's model can be used for rational decision-making when it comes to material and element selection by enabling consistent evaluation of building elements composed of various materials.

This study's model considers the repair cost and the replacement cost of the materials constituting the building elements in the LCC analysis. However, it did not consider the change of physical performance (decreased performance) over time. The physical performance of the building elements gradually decreases with time after construction. Therefore, in future studies, it is necessary to consider the change of physical performance (decreased performance) of the building elements.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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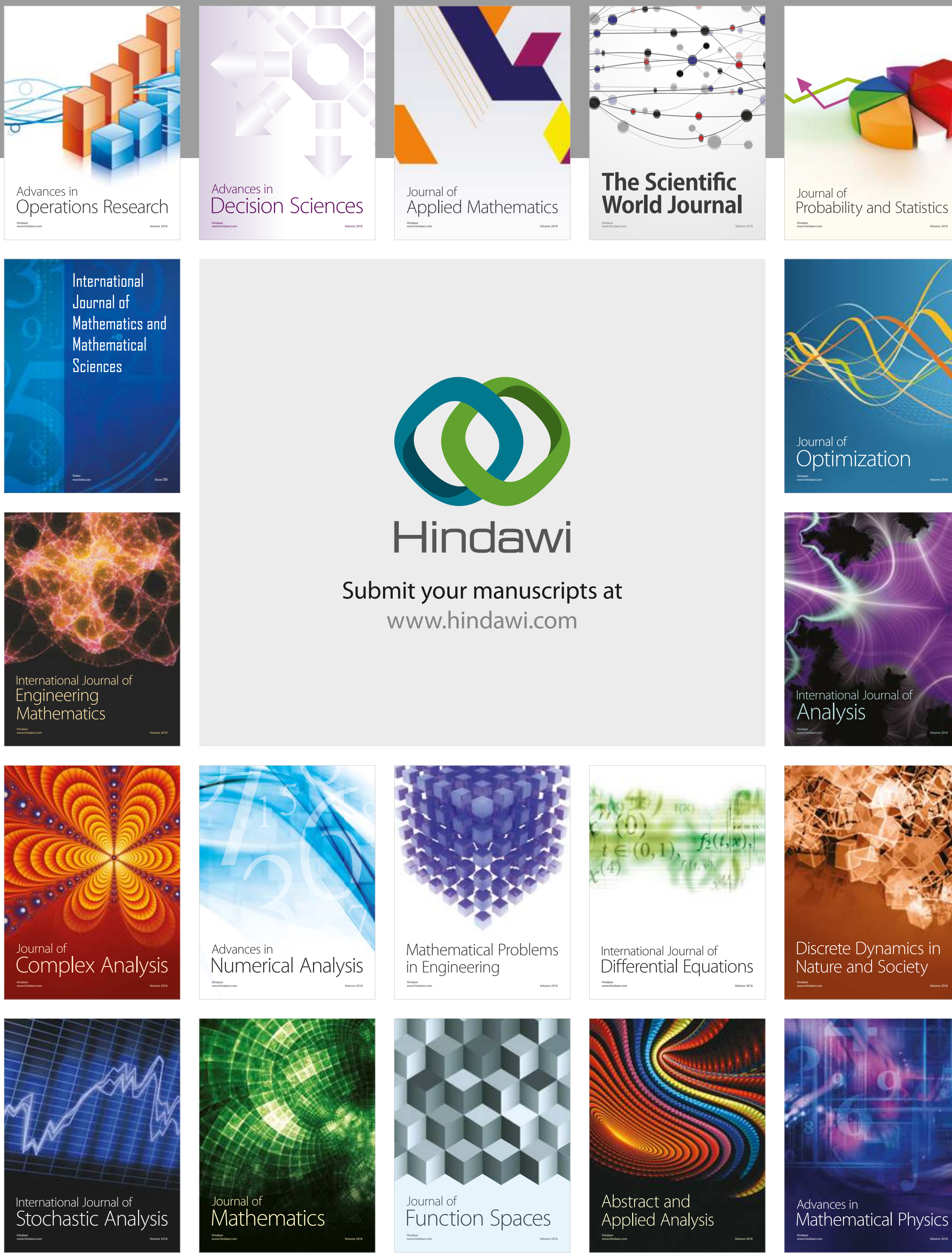
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