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Establishment and Utilization Plans of Apartment Housing Envelope System Database

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Abstract: Recently, apart from the energy saving of new buildings, various carbon-centered environmental policies for climate change were implemented to improve the energy performance of existing buildings, actively promoting green remodeling businesses. This study proposed a classification system for green remodeling envelope systems to select the applicable representative method and input material for the green remodeling of apartment housing. The system boundaries were divided into the material production stage and construction waste processing stage, and the classification system of the envelope system was implemented for applicable green remodeling. A database for the environmental, economic, and energy performances of the classification system was created. Moreover, a green remodeling evaluation sheet system was proposed. According to our results, the economic, energy, and environmental performances of the proposed combinations of the insulation systems were higher than those of the reference combination by 30%, 10%, and 30%, respectively. Regarding the window systems, the economic and energy performances of the proposed input material combinations were higher than those of the reference combination by 22% and 10%, respectively. Additionally, the energy performance of the proposed input material combinations was higher than that of the reference combination by 8~64%.

Keywords: envelope system; green remodeling; database; apartment housing

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1. Introduction

Various carbon-centered environmental policies are implemented to respond to climate change, and the need for a reduction in environmental load caused by industrial activities at the national level is emerging [1]. Consequently, the South Korean government announced the intended nationally determined contributions, a voluntary environmental load reduction goal, to respond to the new climate change regime and has set a detailed goal of a 40% improvement in national energy efficiency by 2030 [2].

In countries where industrialization is in the completion stage, such as South Korea, the proportion of environmental load emissions in the building sector tends to increase much more than in the industrial sector. Currently, in South Korea, the environmental load due to the energy consumption of buildings is gradually increasing, and the energy saving for existing buildings (70% of all buildings) and new buildings is inevitable [3].

Buildings consume large amounts of energy throughout their life cycle. When the energy input in the material production and operation stages of buildings is included, buildings account for 37% of domestic annual energy consumption. Among them, the energy consumption ratio of apartment houses, which are representative of residential buildings, corresponds to approximately 40% of the annual energy consumption of buildings [4]. In the case of high-rise buildings, the area of the envelope increases, and heat loss through the envelope accounts for up to 40% of the total heat loss of the building [5]. Thus, the performance improvement of aged envelope systems is absolutely necessary to improve the energy efficiency of apartment housing through green remodeling.

However, research on apartment housing green remodeling is focused on renewable energy technology with low-cost benefits and on energy consumption in the operation stage; however, the evaluation from the perspective of intrinsic energy, considering building materials used for remodeling, is insufficient. Moreover, database and evaluation technologies to support optimal alternatives in the consideration of energy performance and environmental performance when improving the envelope system of apartment housing are still lacking [6].

Therefore, this study aimed to develop a database of envelope systems for the green remodeling of apartment housing and proposed an evaluation sheet that could utilize the constructed database.

The procedure of this study is to first propose a classification system for the green remodeling envelope system and build a database for the environmental performance, economic performance, and energy performance of the system. For this purpose, usual construction methods and representative input materials, applicable to the actual green remodeling of apartment houses, are selected [7]. In addition, environmental impact assessment is performed for each applied approach and material combination, and economic efficiency and energy performance are analyzed. At this time, the scope of the analysis is set to the material production stage and the construction waste treatment stage generated during construction. It is judged that this can be used as data to efficiently improve envelope performance when remodeling an aging apartment house in the future [8,9].

2. Method and Flow of Research

This study built the classification system and database for applicable green remodeling of apartment houses by separating the assessment phase into the material production phase and processing stage of waste generated during construction in terms of system boundaries [10]. Representative input materials, which are selected by analyzing actual cases of apartment houses and insulation details through 16 kinds of case studies in the green remodeling of apartment houses are analyzed and generated by referring to international standard ISO 21930 (environmental declaration of building products), ISO 14040s (LCA) and European standard EN 15804 for reliable evaluation [11]. A characterization assessment of six environmental impact categories was made for input materials, and an environmental impact DB was established with an environmental impact assessment performed based on domestic and international LCI DB. Regarding the costs of building materials used when remodeling, the standard estimation of construction, transaction price of the Public Procurement Service (second half of 2015) and Korean price information (second half of 2015) were analyzed and a database for costs of supplied construction materials, disposal costs of construction waste and construction cost were created by considering the unit conversion through the country's breakdown cost [12–14].

Additionally, the standard thickness of input materials was referred to through major building material companies, and the input envelope material combination that met the local heat transmission coefficient standards per the "energy-saving building design standard" was established [15]. By leveraging this, it is possible to assess the environmental and economic performances via an input material combination of the outer wall area in the green remodeling envelope system of apartment houses [16,17]. Additionally, the classification system and database of the green remodeling envelope system, which are established by selecting representative construction methods and representative input materials applicable to the actual green remodeling of apartment houses make it possible to improve envelope performance on outer wall areas of existing aged apartment houses, an evaluation sheet of the green remodeling performance, which is available to consider environmental and economic performances of input material combinations in green remodeling envelope system of apartment houses was established through energy performance evaluation and its possibility of application to the standard model in existing aged apartment houses was reviewed through case studies [18,19]. Figure 1 is a flow chart showing the purpose and background of this study.

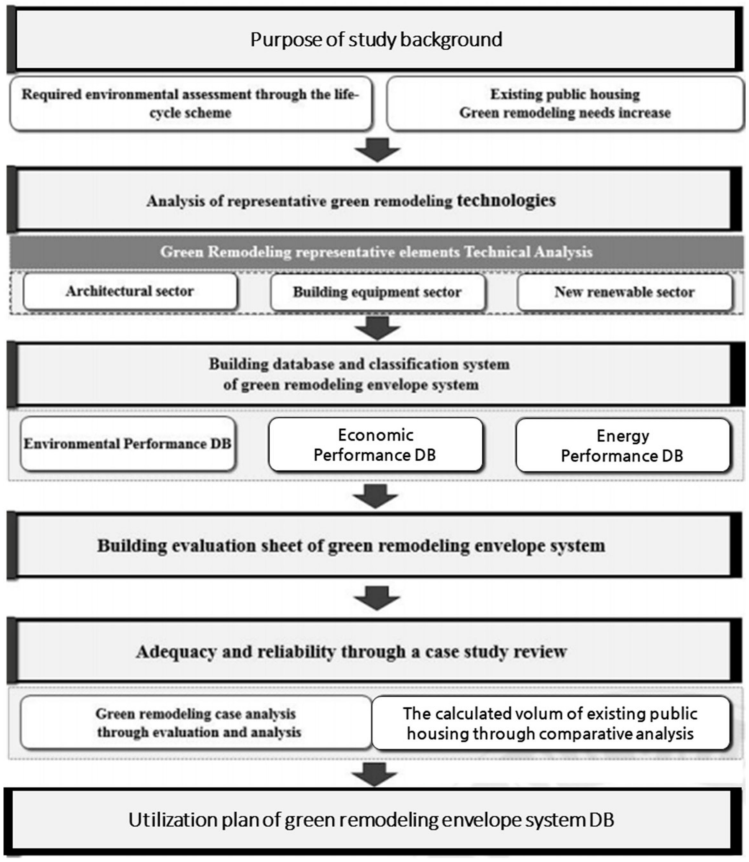


Figure 1. Flowchart of the study.

3. Technology Trends of Green Remodeling Envelope Systems

Analysis of Representative Green Remodeling Technologies

Green remodeling is employed to reduce energy consumption in order to improve the energy efficiency of buildings, either for major repair or for a partial extension to satisfy environmentally friendly construction standards [20]. Representative element technologies for green remodeling were analyzed through domestic and overseas literature reviews. The element technologies can be largely classified into construction, equipment, and renewable energy fields [21]. Furthermore, element technologies can be selected according to passive and active elements dependent on the target classification [22].

The applicable representative element technologies were analyzed by examining actual green remodeling cases (Table 1). In the case of envelope systems, most studies focused on the improvement of energy performance, although they had a large impact on the reduction in environmental load. Moreover, studies on the classification system and database building according to input materials were insufficient in the actual application of green remodeling element technologies [23,24].

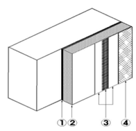
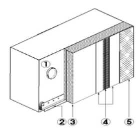
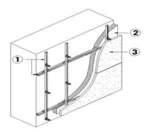
Table 1. Analysis of representative element technologies for domestic green remodeling [25].

Classification	Building Area	Target Classification	Selection of Element Technologies	Representative Element Technologies	Details	Reduction in Environmental Load	Construction of Environmental Impact DB
Construction field	Outside	Insulation Windows Airtightness Exterior finish External awning	Envelope system	High thermal insulation system	- Legal standard insulation thickness: 85 mm or larger - Passive house standard insulation thickness: 213 mm - Based on EPS type 2 No. 1 (0.032 W/m·k)	●	○
				High-performance window system	- Composition (glass + window frame) - Low-E triple glass - High insulation frame	●	○
Equipment field	Inside	Lighting equipment Boiler Ventilation Cooling and heating systems	High-efficiency equipment	Lighting energy-saving system	- High-efficiency FLs (2/28 W) - Replacement with high-efficiency LED lamps	○	◐
				Heat source air-conditioning system	- System changes for existing heat sources - System changes for existing cold heat sources	●	◐
Renewable field	Inside and outside	Solar photovoltaic equipment Solar heat equipment	Renewable energy	Solar photovoltaic system	- Clean energy source with long life (>20 y) - Limited installation sites and high system cost	◐	◐
		Geothermal equipment		Solar heat system	- Used for heating and cooling of buildings and hot water supply. Because energy varies greatly with season and time, heat collection and storage technologies are vital.	◐	◐
		Fuel cells		Geothermal system	- Temperature differences of ground water and underground heat are used for cooling and heating.	◐	◐

●: strong; ◐: average; ○: weak; FL: fluorescent lamp; LED: light-emitting diode; DB: Data Base3.2 analysis of green remodeling envelope system.

In this study, apartment housings were selected as target buildings for the analysis of the green remodeling envelope system. Because the outer shell is the most important part of the insulation in the apartment, it is essential to improve the performance of the passive elements, such as exterior walls and windows, for energy efficiency. The outer wall insulation of apartment housing can be divided into interior insulation, middle insulation, and exterior insulation. In South Korea, it is recommended that exterior insulation is applied, such as by attaching additional points, when calculating the energy performance index (EPI) according to the area ratio. Applying an exterior insulation can fundamentally block thermal bridges in accordance with the strengthening of energy performance standards. The exterior insulation methods are largely classified into wet, dry, and vented methods according to the structure bonding method, as shown in Table 2. In the wet method, insulation materials are attached using an adhesive; in the dry method, insulation materials are constructed using a reinforcing material. [26]. When applied to high-rise apartment buildings, the wet method should consider an additional reinforcement [27].

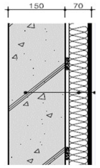
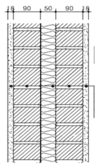
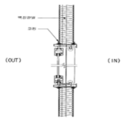
Table 2. Insulation system methods and application status.

Classification	Classification by Structural Insulation and Bonding Method		
	Wet	**Dry**	**Vented**
Concept diagram			
Composition	Adhesive	Adhesive	Adhesive
	Insulation	Track	Insulation
	Reinforcing mesh	Insulation	Finishing material
	Finishing material	④	-
	-	⑤	-
Site	General exterior wall	General exterior wall	Stone exterior wall
Applications	Bonding method (fasteners, studs) Upper floors can be constructed through wet method	Track method High floors of apartment housing can be constructed	Low floors of apartment housing can be constructed

Regarding domestic and foreign insulation specifications, there are regulations according to the conditions of Korea standard (KS), European technical approval guidelines, and German industrial standards. However, when the insulation methods are applied in Korea, only basic information on the application of input materials and the construction method according to the material cost and construction cost is provided in most construction projects [28].

Therefore, this study analyzed 16 cases of old apartment housing for which green remodeling was performed for the detailed analysis of the method and materials applied to green remodeling envelope systems. The representative cases are listed in Table 3. The input materials were analyzed by the following application methods: Alternative 1 (keep existing condition + add insulation), Alternative 2 (demolish existing condition + new insulation), and Alternative 3 (demolish existing condition + new insulation + add insulation). These methods were applied according to the remodeling method of interior and exterior insulations for alternative methods of improving the insulation systems in old apartment housings. The window systems were also analyzed by Alternative 1 (keep existing condition + add windows) and Alternative 2 (demolish existing condition + new windows).

Table 3. Improvement cases for green remodeling apartment housing envelope system.

Exterior Walls of Old Apartment Housing			Green Remodeling Application Cases					
Interior insulation of exterior wall combination case 	No.	Detailed materials	Alternative 1	Add interior insulation	Alternative 2	Demolish existing condition + new insulation	Alternative 3	Demolish existing condition + add insulation
			No.	Materials	No.	Materials	No.	Materials
	1	Concrete	1	Concrete	1	Concrete	1	Concrete
	2	T50 rock wool	2	T50 rock wool	2	(demolish)	2	(demolish)
	3	Gypsum board	3	Gypsum board	3	(demolish)	3	(demolish)
	4	Wallpaper	4	Extrusion method type 2	4	Bead method type 2	4	Bead method type 2
	5	-	5	Gypsum board	5	Gypsum board	5	Gypsum board
	6	-	6	Wallpaper	6	Wallpaper	6	Wallpaper
	7	-	7	-	7	-	7	Insulation mortar
	8	-	8	-	8	-	8	Water-based paint
Middle insulation of exterior wall combination case 	No.	Detailed materials	Alternative 1	Add exterior insulation	Alternative 2	Demolish existing condition + new insulation	Alternative 3	Add interior insulation
			No.	Materials	No.	Materials	No.	Materials
	1	Cement mortar	1	Cement mortar	1	Cement mortar	1	Cement mortar
	2	Cement brick	2	Cement brick	2	Cement brick	2	Cement brick
	3	Rock wool	3	Rock wool	3	(demolish)	3	Rock wool
	4	Cement brick	4	Cement brick	4	(demolish)	4	Cement brick
	5	Cement mortar	5	Cement mortar	5	(demolish)	5	Cement mortar
	6	-	6	Bead method type 2	6	Bead method type 2	6	Bead method type 2
	7	-	7	Gypsum board	7	Gypsum board	7	Gypsum board
	8	-	8	Cement mortar	8	Wallpaper	8	Wallpaper
Existing window case 	No.	Detailed materials	Alternative 1	Keep existing windows + add windows	Alternative 2	Demolish existing windows + new windows		
			No.	Materials	No.	Materials		
	1	Clear glass	1	Clear glass	1	(demolish)		
	2	Wooden frame	2	Wooden frame	2	(demolish)		
	3	-	3	Double glazing	3	Double glazing		
	4	-	4	Low-E double glass	4	Low-E double glass		
	5	-	5	PVC frame	5	PVC frame		

PVC: polyvinyl chloride.

Consequently, the remodeling methods can be classified into replacement and add-on methods; the former refers to the demolition of the existing method in an old apartment housing envelope system, whereas the latter refers to the supplementation of the existing method. Similarly, window remodeling methods can be classified into the replacement method, which replaces the old windows with high-efficiency windows, and the add-on method, which adds high-efficiency windows to the existing windows. This allows the selection of representative input materials according to the representative method for each green remodeling application method [29].

4. Construction of Green Remodeling Envelope System Database and Classification System

4.1. Overview

A classification system for green remodeling envelope systems applicable to the interior and middle insulations of existing apartment housing was constructed by dividing the insulation methods into wet and dry methods. We analyzed the detailed finished insulation diagrams according to green remodeling application cases and the literature review. For the representative input materials, the exterior wall and window materials were selected through the classification system [30]. As for the insulation materials, which have the highest importance for insulation performance, a database of 16 types by density-of-bead-method insulation board types 1 and 2, extrusion method insulation boards, and glass wool was built for performance. In the case of insulation thickness, a database that measured from 80 mm to 240 mm of each insulation material was built by referring to construction material companies and building energy-saving design criteria to satisfy the various requirements of users. In addition, the thicknesses of windows were divided into 18 mm, 22 mm, and 24 mm, which are the thicknesses most commonly used in domestic construction material companies, according to Korea price information and transaction information from the public procurement service [31]. The frame thicknesses of the single-, double-, and triple-glazed windows were selected as 140 mm, 280 mm, and 470 mm, respectively. Through this process, a database of the environmental, economic, and energy performance of the selected representative input materials and other materials was built. Moreover, a database of input material combinations was built by classifying green remodeling application methods into add-on methods and replacement methods [32].

4.2. Construction of the Classification System for Green Remodeling Envelope Systems

In this study, a classification system for envelope systems, which are representative of green remodeling technology applicable to old apartment housings, was built as shown in Figure 2. The envelope systems were largely classified into insulation systems and window systems applicable to exterior walls. Furthermore, the green remodeling application methods for apartment housings were classified into add-on (keep existing condition + add insulation) and replacement (demolish existing condition + new insulation) methods. Accordingly, the representative materials were selected through the classification of dry and wet methods, and a database of the selected input material combinations was built. This construction method is a method generally used when performing remodeling work, and for the combination of materials, reference was made to the green remodeling technology of the building envelope system in the existing literature [33]. In this study, exterior wall and window materials were selected as the representative materials with the largest impact on the envelope performance. In the case of the insulation system, for each CaseX, combinations of insulation, finishing, and other materials were established. In addition, the window systems were classified into single-, double-, and triple-glazed windows, and combinations of windows and frames were established for each CaseY.

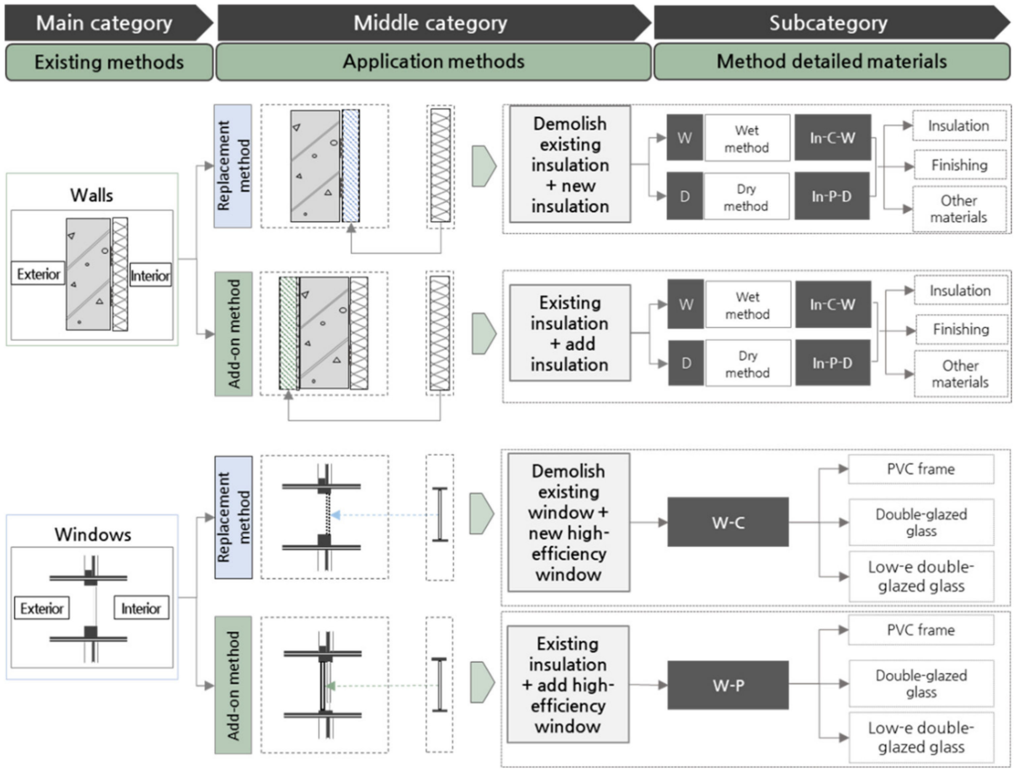


Figure 2. Classification system for green remodeling envelope systems.

4.3. Building an Environmental Performance Database

The system boundaries for environmental performance were divided into the material production stage and construction waste processing stage for wastes generated during construction. The replacement and add-on methods were separately applied considering the classification system presented in Figure 2. For the replacement and add-on methods, 550 and 1090 environmental performance database combinations were established for each case, respectively.

A database of environmental impact characterization values for environmental impact categories on building materials is necessary to evaluate the whole process of a building. Building owners and architects can easily assess the environmental impact of a building by multiplying the quantity of major building materials input to the building by the environmental impact characterization value. The environmental impact can be assessed by using Equation (1) [34]:

$$CI_i = \sum CI_{i,j} = \sum (Load_j \times eqv_{i,j}) \quad (1)$$

CI_i: Impact of an item (j) included in the impact category i;
$CI_{i,j}$: Impact of the *j*th item on the impact category i;
$Load_j$: Environmental load of the *j*th item;
$eqv_{i,j}$: Analysis value for the characterization coefficient of the *j*th item belonging to the impact category i.

Furthermore, we investigated the current status of the national LCI (life cycle inventory) DB (Ministry of Knowledge Economy, Ministry of Environment) and the national database on the environmental information of building materials (Ministry of Land, Transport, and Maritime Affairs), established by the individual integration method to calculate the highly reliable environmental impact characterization values of major building materials. Subsequently, the national LCI DB was first applied depending on whether the national LCI database was certified. The LCI database of detailed building materials was not established in the national LCI DB; the study was researched in a supplementary way by applying the national DB of the environmental information of building materials and the overseas LCI DB.

4.4. Building an Economic Performance Database

To build a database of economic performance, the detailed input materials in the material production and construction waste processing stages were considered. The cost of building materials used in green remodeling was determined by the construction standard calculation, the transaction price of the public procurement service (second half of 2015), and the Korea price information (second half of 2015). The database matching operation was performed by analyzing domestic cost breakdown through unit conversion work for input materials using Equation (2):

$$E_c = \sum (Q_{m,i} \times l_{m,i} + D_{m,i} \times l_{m,i} + C_m) \quad (2)$$

$Q_{m,i}$: quantity (i) and price (m) of input construction materials;
$D_{m,i}$: quantity (i) and price (m) of construction waste materials;
C_m: Construction cost (m);
$l_{m,i}$: Basic unit of input construction materials.

A database on the cost of self-assessment for the green remodeling of apartment housing and construction waste generated during demolition was constructed using the intermediate processing cost of construction waste provided by the Korean price information and the building material code of public procurement service, as well as the cost of input materials provided by Korean price information. In addition, an economic performance database for a total of 291 input materials was constructed by dividing the replacement and add-on methods and distinguishing the market construction price code provided by the public procurement service and the construction cost provided by Korean price information. The replacement method also generated a construction waste processing cost. For the add-on method, the database was built by analyzing the material unit and construction costs.

4.5. Building an Energy Performance Database

In the case of the insulation systems, the thermal transmittance value according to the insulation thickness (80–240 mm) was applied by analyzing the thermal conductivity presented in the KS and the building energy-saving design criteria of South Korea. Furthermore, the thermal transmittance value for the insulation performances of windows and doors presented in the building energy-saving design criteria were applied, and the appropriateness of the values was reviewed by a comparative analysis with the window thermal transmittance value for each company suggested in the energy efficiency rating system of the Korea Energy Agency. The thickness of the air layer was limited to 6 mm, and the thermal transmittance values for each of the ordinary glass and low-E glass according to single-, double-, and triple-glazed windows were applied based on metal and plastic frames. Furthermore, the heat resistance value of the input materials can be derived from Equation (3). The thermal transmittance value of construction parts can be derived from Equation (4), considering the heat transfer resistance values of the indoor and outdoor surfaces in case of facing the outside air:

$$a_1 = \frac{T}{K} \quad (3)$$

$$U = \frac{1}{R_i + \sum_{a_1}^{a_n} (a_1 + a_n) + R_o} \quad (4)$$

U: Thermal transmittance (W/m^2K);
R_i: Heat transfer resistance of indoor surface (m^2K/W);

R_o: Heat transfer resistance of outdoor surface (m^2K/W);
a_1: Heat resistance (m^2K/W);
K: Thermal conductivity(W/mk);
T: Material thickness (mm).

5. Utilization of Green Remodeling Envelope System Database

5.1. Overview

In this study, an evaluation sheet that could be used to improve the envelope for the green remodeling of apartment housing was proposed through various performance databases for the input materials of the envelope system constructed above. The proposed databases were built as shown in Tables 4 and 5. The envelope system input material combinations were composed of CaseX for the insulation system and CaseY for the window system. In the case of the replacement (C) and add-on (P) methods, which are green remodeling application methods, the user convenience for selection by case was improved through the symbols for the dry (D) and wet (W) methods. Furthermore, the databases were built to enable a thermal transmittance equivalent to or greater than the current target energy performance standard through the input of thermal transmittance values for exterior wall materials and window materials by the orientation of old apartment housing. Moreover, the databases were built to enable average thermal transmittance values when the user enters the area value for the building part. To select input material combinations for the green remodeling envelope system, a utilization method of envelope system database was presented by providing information about environmental and economic performance according to the thermal transmittance value obtained through databases on the environmental, economic, and energy performance for a total of 40,000 input material combinations for the entire envelope system constructed (Tables 4 and 5). Figure 3 presents the composition of the proposed evaluation sheet. This evaluation system is based on direct user input and can perform evaluation through the input of areas by direction (front, rear, and side) and thermal transmittance values for the input materials by building part (W and G).

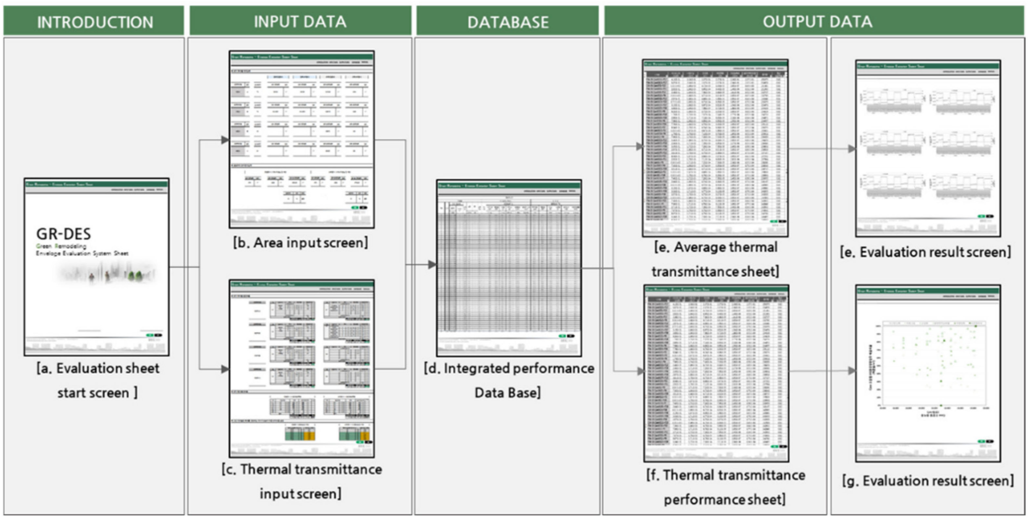


Figure 3. Composition of evaluation sheet for green remodeling envelope system.

Table 4. Database construction for input material combinations of green remodeling insulation system.

Green Remodeling Envelope System Application Method						Top Six Environmental Impact Categories							Economic Performance	Energy Performance
Main categories	Middle categories	Subcategories	Method classification	Classification of other combination materials	Compositions of material combinations	Classification code	Global warming (GWP)	Resource depletion (ADP)	Acidification (AP)	Eutrophication (EP)	Ozone layer depletion (ODP)	Photochemical oxide (POCP)	Total cost	Thermal transmittance
						CaseX	CO_{2eq}	1	SO_{2eq}	PO_43_{-eq}	CFC_{-11eq}	$Ethylene_{eq}$	(KRW)	(W/m²K)
Replacement method	Demolish existing interior insulation + new insulation	New interior insulation	Dry method	Stud	Bead method type 1 No. 1	C-In-D-$CaseX_1$	$2.\ 19 \times 10^{-3}$	6.25×10^{-6}	3.08×10	2.08×10^{-6}	4.82×10^{-10}	3.02×10^{-6}	597,944	0.06
					Bead method type 2 No. 1	C-In-D-$CaseX_{69}$	2.19×10^{-3}	6.25×10^{-6}	3.08×10	2.08×10^{-6}	4.82×10^{-10}	3.02×10^{-6}	597,481	0.10
				Gypsum board	Extruded polystyrene special	C-In-D-$CaseX_{137}$	2.18×10^{-3}	6.25×10^{-6}	5.11	2.08×10^{-6}	2.24×10^{-10}	3.02×10^{-6}	601,545	0.10
					Glass wool	C-In-D-$CaseX_{205}$	2.18×10^{-3}	6.24×10^{-6}	3.31	2.08×10^{-6}	2.24×10^{-10}	3.02×10^{-6}	599,938	0.11
			Wet method	Adhesive	Bead method type 1 No. 1	C-In-W-$CaseX_1$	2.19×10^{-3}	6.11×10^{-6}	1.23×10^{-5}	2.08×10^{-6}	4.82×10^{-10}	3.00×10^{-6}	184,668	0.22
					Bead method type 2 No. 1	C-In-W-$CaseX_{70}$	2.19×10^{-3}	6.11×10^{-6}	1.23×10^{-5}	2.08×10^{-6}	5.14×10^{-10}	3.00×10^{-6}	189,213	0.19
				Gypsum board	Extrusion method thermal insulation plate special	C-In-W-$CaseX_{138}$	2.18×10^{-3}	6.10×10^{-6}	1.23×10^{-5}	2.08×10^{-6}	2.24×10^{-10}	3.00×10^{-6}	192,079	0.18
					Glass wool	C-In-W-$CaseX_{206}$	2.17×10^{-3}	6.10×10^{-6}	1.23×10^{-5}	2.08×10^{-6}	2.23×10^{-10}	3.00×10^{-6}	191,648	0.24
Add-on method	Existing interior insulation + add exterior insulation	Add interior insulation	Dry method	PVC track	Bead method type 1 No. 1	P-In-D-$CaseX_1$	2.01×10^{-4}	7.11×10^{-5}	7.11×10^{-5}	7.11×10^{-5}	7.10×10^{-5}	7.10×10^{-5}	221,502	0.06
				Resin finish	Bead method type 2 No. 1	P-In-D-$CaseX_{69}$	2.01×10^{-4}	7.11×10^{-5}	7.11×10^{-5}	7.11×10^{-5}	7.10×10^{-5}	7.10×10^{-5}	221,039	0.06
				Mortar finish	Extrusion method thermal insulation plate special	P-In-D-$CaseX_{137}$	1.91×10^{-4}	7.11×10^{-5}	7.11×10^{-5}	7.11×10^{-5}	7.10×10^{-5}	7.10×10^{-5}	225,103	0.06
					Glass wool	P-In-D-$CaseX_{205}$	1.90×10^{-4}	7.11×10^{-5}	7.11×10^{-5}	7.11×10^{-5}	7.10×10^{-5}	7.10×10^{-5}	223,496	0.07
			Wet method	Adhesive	Bead method type 1 No. 1	P-In-W-$CaseX_1$	2.12×10^{-5}	3.76×10^{-7}	3.66×10^{-7}	3.12×10^{-7}	3.02×10^{-7}	3.06×10^{-7}	132,507	0.05
				Fastener	Bead method type 2 No. 1	P-In-W-$CaseX_{69}$	2.12×10^{-5}	3.76×10^{-7}	3.66×10^{-7}	3.12×10^{-7}	3.02×10^{-7}	3.06×10^{-7}	132,044	0.05
				Resin finish	Extrusion method thermal insulation plate special	P-In-W-$CaseX_{134}$	2.54×10^{-5}	3.81×10^{-7}	3.69×10^{-7}	3.12×10^{-7}	3.02×10^{-7}	3.06×10^{-7}	167,456	0.04
				Mortar finish	Glass wool	P-In-W-$CaseX_{202}$	1.15×10^{-5}	3.79×10^{-7}	3.61×10^{-7}	3.11×10^{-7}	3.02×10^{-7}	3.10×10^{-7}	180 058	0.04

GWP: global warming potential; ADP: resource depletion potential; AP: acidification potential; EP: eutrophication potential; ODP: ozone layer depletion potential; POCP: photochemical oxide potential; CFC: chlorofluorocarbon.

Table 5. Construction of input material combinations for green remodeling window systems.

Green Remodeling Envelope System Application Method						**Top Six Environmental Impact Categories**						**Economic Performance**	**Energy Performance**
Main categories	Middle categories	Subcategories	Window classification	Composition of the number of material combinations	Classification code	Global warming (GWP)	Resource depletion (ADP)	Acidification (AP)	Eutrophication (EP)	Ozone layer depletion (ODP)	Photochemical oxide (POCP)	Total cost	Thermal transmittance
				Detailed composition	CaseY	CO_{2eq}	C_2H_2	SO_{2eq}	$PO_43_{\text{-}eq}$	$CFC_{\text{-}11eq}$	$Ethylene_{eq}$	(KRW)	(W/m^2K)
Replacement method	Demolish existing windows + new windows	New high-efficiency windows	Single-glazed	6CL + 6Air + 6CL	W-$CaseY_1$	1.16×10^{-1}	4.73×10^{-4}	1.58×10^{-4}	1.15×10^{-5}	9.50×10^{-10}	2.79×10^{-4}	187,103	3.10
				6CL + 6Air + 6LE	W-$CaseY_4$	1.16×10^{-1}	4.73×10^{-4}	1.58×10^{-4}	1.15×10^{-5}	9.50×10^{-10}	2.79×10^{-4}	211,703	2.60
			Double-glazed	6CL + 6Air + 6CL + 6CL + 6Air + 6CL	W-$CaseY_7$	2.32×10^{-1}	9.46×10^{-4}	3.16×10^{-4}	2.31×10^{-5}	1.90×10^{-7}	5.58×10^{-4}	258,105	1.03
				6CL + 6Air + 6LE + 6CL + 6Air + 6LE	W-$CaseY_{10}$	2.32×10^{-1}	9.46×10^{-4}	3.16×10^{-4}	2.31×10^{-5}	1.90×10^{-7}	5.58×10^{-4}	378,624	0.87
			Tripe-glazed	6CL + 6Air + 6CL + 6CL + 6Air + 6CL + 6CL + 6Air + 6CL	W-$CaseY_{16}$	3.48×10^{-1}	1.42×10^{-3}	4.74×10^{-4}	3.46×10^{-5}	2.85×10^{-7}	8.37×10^{-4}	825,630	0.53
				6CL + 6Air + 6LE + 6CL + 6Air + 6LE + 6CL + 6Air + 6LE	W-$CaseY_{16}$	3.48×10^{-1}	1.42×10^{-3}	4.74×10^{-4}	3.46×10^{-5}	2.85×10^{-7}	8.37×10^{-4}	1,141,293	0.46
Add-on method	Keep existing condition + add windows	Add high-efficiency windows	Single-glazed	6CL+6Air+6CL	W-$CaseY_{19}$	1.16×10^{-1}	4.73×10^{-4}	1.58×10^{-4}	1.15×10^{-5}	9.36×10^{-10}	2.79×10^{-4}	187,090	3.10
				6CL + 6Air + 6LE	W-$CaseY_{22}$	1.16×10^{-1}	4.73×10^{-4}	1.58×10^{-4}	1.15×10^{-5}	9.36×10^{-10}	2.79×10^{-4}	211,690	2.60
			Double-glazed	6CL + 6Air + 6CL + 6CL + 6Air + 6CL	W-$CaseY_{25}$	2.32×10^{-1}	9.45×10^{-4}	3.15×10^{-4}	2.29×10^{-5}	1.87×10^{-7}	5.58×10^{-4}	329,400	1.03
				6CL + 6Air + 6LE + 6CL + 6Air + 6LE	W-CaseY28	2.32×10^{-1}	9.45×10^{-4}	3.15×10^{-4}	2.29×10^{-5}	1.87×10^{-7}	5.58×10^{-4}	378,600	0.87

5.2. Composition of Evaluation Sheet for Green Remodeling Envelope System

(1) Area/thermal transmittance input stage:

The user can evaluate the envelope part of the apartment housing by (b) inputting the area of each building orientation, and the suitability of the energy performance standard of the current legal standard can be determined by inputting the thermal transmittance value for (b) the input materials of each part. Furthermore, the ratio of window area to the total envelope area input can be considered, and the average thermal transmittance value can be derived, which allows the energy performance of different parts to be considered. This can facilitate the evaluation of apartment housing in the architectural part of EPI because the average thermal transmittance and exterior insulation application accounts for more than 40% of the total score in the evaluation of scoring in apartment housing presented by the EPI in the building energy-saving design criteria.

(2) Integrated performance database utilization stage:

An (d) integrated performance database was constructed, which enabled the integrated analysis of the databases of environmental, economic, and energy performance for green remodeling envelope system input material combinations per unit area through the input of area by building direction and the thermal transmittance values for input materials. Through this database, each performance can be evaluated, and input material combinations according to the integrated performance of the green remodeling envelope system can be proposed, such as (e) evaluation results screen and (f) evaluation result screen. In other words, the proposed evaluation sheet for green remodeling envelope system enables the consideration of six environmental and economic performances according to the target energy performance of the user through the basic input values for old apartment housing. This can be used to propose alternatives for input material combinations of green remodeling envelope systems according to the reinforcement of energy performance standards in the future.

(3) Evaluation result stage:

As shown in the following (e) and (f) evaluation result screens, input material combinations for six environmental impacts and economic performances can be derived according to the thermal transmittance values and average thermal transmittance values from the evaluation result of the evaluation sheet proposed in this study. Through the input of thermal transmittance values for input materials and area for each building part for existing apartment housing, users can choose the input material combinations of the envelope system for average thermal transmittance according to target energy performance and for environmental and economic performance according to thermal transmittance. In other words, methods for deriving the average thermal transmittance and evaluating thermal transmittance for each area were constructed by considering the energy performance for different areas through area input.

6. Case Analysis

6.1. Setting Evaluation Target

In this study, the applicability of the evaluation sheet for the green remodeling envelope system was reviewed, and the input material combinations of the improved envelope system were analyzed to suggest the use of the constructed envelope system database for cases where green remodeling projects were performed. The building to be evaluated is a 19-year-old apartment housing located in Eunpyeong-gu, Seoul, which was constructed in 1997 (Table 6). There are five buildings in the apartment complex, and the walls are made of reinforced concrete. Green remodeling was performed for building No. 102. The green remodeling work of the insulation system was conducted for the side walls, which directly face the outside air; for the remodeling work of the window system, the windows on the front and rear surfaces were replaced.

Table 6. Construction outline.

Project Name	**00 Apartment Housing Green Remodeling Work (Building No. 102)**		
Number of households	445 households	Area for exclusive use	5947.97 m^2
Heating method	Individual heating	Floor area ratio	242%
Construction period	4 months	Number of floors	12–15
Year of construction	September 1997	Structure	Reinforced concrete

6.2. Analysis of Evaluation Case

(1) Analysis of building to be evaluated:

The case analysis result showed that exterior insulation materials were added to the existing interior insulation materials. The existing combination consisted of fastener + bead method type 2 No. 1 + mortar finish. The thermal transmittance of the input material combination according to the insulation system was 0.25 W/m^2K. This satisfied the criterion of 0.27 W/m^2K for the central region when the apartment housing directly faced the outside air, which was the legal permission criterion for energy performance in 2014. However, it did not satisfy the 2016 criterion of 0.21 W/m^2K. Furthermore, the replacement method was applied for the 38 mm (5CL + 12Air + 5LE + 5CL + 6Air + 5CL, CL: clear; LE: low-e coating) double-glazed window at the front and 24 mm (5CL + 10Air + 5LE) single-glazed window at the rear of the existing windows. The thermal transmittance values were 1.35 and 1.02 W/m^2K, respectively. The double-glazed windows satisfied the 2014 criterion, 1.5 W/m^2K, and the 2016 criterion, 1.2 W/m^2K. However, the single-glazed window did not satisfy the 2016 criterion.

(2) Analysis of insulation system alternatives:

As a result of comparing the environmental impact and economic performance values per unit of area calculated through the proposed evaluation sheet, with the reference combination calculated through the volume calculation statement and the detailed insulation finish diagram, the distribution in Figure 4 was obtained. The top combinations can be considered through an analysis of the environmental and economic performance according to energy performance. Among a total of 1090 input material combinations of the add-on method in the proposed evaluation sheet, the input material combinations that had an energy performance higher than 0.25 W/m^2K of the compared reference combination (fastener + bead method type 2 No. 1 + mortar finish) were selected first. Furthermore, the input material combinations of the green remodeling insulation system with performances higher than the six environmental impacts—GWP 8.53×10^{-3} (CO_{2eq}/m^2), ADP 1.21×10^{-5} (C_2H_2/m^2), AP 9.98×10^{-6} (SO_{2eq}/m^2), EP 33×10^{-6} ($PO_43_{\text{-eq}}/m^2$), ODP 3.21×10^{-11} ($CFC_{\text{-11eq}}/m^2$), and 1.61×10^{-6} ($ethylene_{\text{-eq}}/m^2$)—were proposed for 60 input material combinations with a performance higher than 27,324 (1000 KRW/m^2), which was the existing economic performance (Table 7).

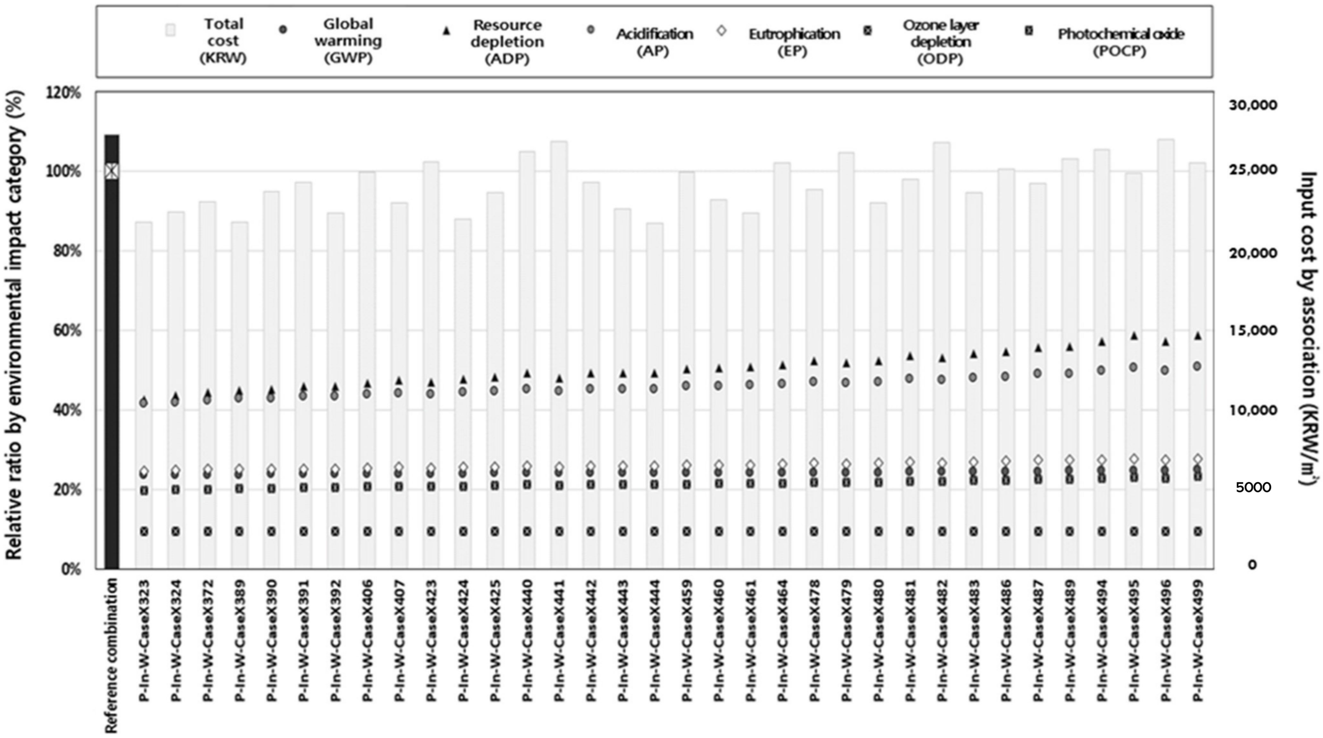


Figure 4. Case analysis of green remodeling envelope system input material combinations.

Table 7. Analysis result for input material combinations of the green remodeling envelope system.

CaseX	**Global Warming**	**Cost**	**CaseX**	**Resource Depletion**	**Cost**
Insulation system	CO_{2eq}/m^2	1000 KRW/m^2	Insulation system	C_2H_2/m^2	1000 KRW/m^2
Reference combination	9.21×10^{-3}	27,324	Reference combination	1.21×10^{-5}	27,324
P-In-W-CaseX$_{323}$	2.00×10^{-3}	21,823	P-In-W-CaseX$_{323}$	5.16×10^{-6}	21,823
	59 other types			59 other types	
CaseX	Acidification	Cost	CaseX	Eutrophication	Cost
Insulation system	SO_{2eq}/m^2	1000 KRW/m^2	Insulation system	$PO_43_{\text{-eq}}/m^2$	1000 KRW/m^2
Reference combination	9.94×10^{-6}	27,324	Reference combination	4.28×10^{-6}	27,324
P-In-W-CaseX$_{323}$	4.13×10^{-6}	21,823	P-In-W-CaseX$_{323}$	1.06×10^{-6}	21,823
	59 other types			59 other types	
CaseX	Ozone layer depletion	Cost	CaseX	Photochemical oxide	Cost
Insulation system	$CFC_{\text{-11eq}}/m^2$	1000 KRW/m^2	Insulation system	Ethyleneeq/m^2	1000 KRW/m^2
Reference combination	3.23×10^{-6}	27,324	Reference combination	4.12×10^{-6}	27,324
P-In-W-CaseX$_{323}$	3.02×10^{-7}	21,823	P-In-W-CaseX$_{323}$	7.99×10^{-7}	21,823
	59 other types			59 other types	
CaseY	Global warming	Cost	CaseY	Resource depletion	Cost
Window system	CO_{2eq}/m^2	1000 KRW/m^2	Window system	C_2H_2/m^2	1000 KRW/m^2
Reference combination	3.32×10^{-1}	44,355	Reference combination	9.85×10^{-2}	44,355
W-CaseY8	6.12×10^{-1}	30,500	W-CaseY8	1.97×10^{-1}	30,500
	4 other types			4 other types	

Table 7. *Cont.*

CaseY	Acidification	Cost	CaseY	Eutrophication	Cost
Window system	SO_{2eq}/m^2	1000 KRW/m^2	Window system	$PO43_{\text{-eq}}/m^2$	1000 KRW/m^2
Reference combination	3.32×10^{-1}	44,355	Reference combination	9.85×10^{-2}	44,355
W-CaseY8	1.94×10^{-1}	30,500	W-CaseY8	1.93×10^{-1}	30,500
	4 other types			4 other types	
CaseY	Ozone layer depletion	Cost	CaseY	Photochemical oxide	Cost
Window system	$CFC_{\text{-11eq}}/m^2$	1000 KRW/m^2	Window system	$CFC_{\text{-11eq}}/m^2$	1000 KRW/m^2
Reference combination	3.32×10^{-1}	44,355	Reference combination	9.85×10^{-2}	44,355
W-CaseY8	1.93×10^{-1}	30,500	W-CaseY8	1.94×10^{-1}	30,500
	2 other types			4 other types	

(3) Analysis of window system alternatives:

Among a total of 30 input material combinations applicable to the proposed evaluation sheet, the single- and double-glazed windows, which are input materials for the window replacement and the add-on method for the compared existing windows, were analyzed.

The input material combinations with a thermal transmittance higher than 0.25 W/m^2K and an economic performance higher than the compared reference combination among 30 input material combinations of the add-on method were first selected using the proposed evaluation sheet. The five combinations of the replacement method were proposed (Table 7).

(4) Overall analysis:

As a result of the detailed analysis of the reference combination for the insulation system and the material combination presented in this study, it was found that the economic and energy performance of the combination P-D-CaseX (polyvinyl chloride (PVC) track + bead method type 2 No. 1 + resin finish), which is a dry method of the add-on method, increased by 30% and 10%, respectively, compared to the combination of the existing case. The reduction rates of the six environmental performances for the bead method type 1 No. 4 in comparison with those of the bead method type 2 No. 1 were identified. It was found that the evaluation results of the bead method type 1 No. 4 showed a reduction rate of 30% compared to those of the bead method type 2 No. 1. In the case of the window system replacement method, the input material combinations with economic and energy performances higher than those of the existing cases were selected first. The combination of PVC frames and double glazing, W-CaseY8 (5CL + 10Air + 5CL + 5CL + 10Air + 5CL), showed an economic performance higher by 22% and an energy performance higher by 10% than those of the reference combination. In the case of the add-on method, six input material combinations were suggested to satisfy the current criteria. The energy performance of the proposed input material combinations was higher than that of the reference combination by between 8% and 64%. They satisfied the current legal criteria and could allow us to prepare for higher energy performance criteria in the future.

7. Conclusions

This study built databases of the envelope system for the green remodeling of apartment housing and proposed an evaluation sheet for green remodeling envelope systems that could use the constructed databases. The following conclusions were obtained.

A classification system of green remodeling envelope systems was constructed by analyzing actual cases of green remodeling projects of apartment housing, and the representative input materials were selected according to the remodeling application methods.

Through this study, databases for 550 and 1090 input material combinations of green remodeling envelope systems were separately constructed for the replacement method and add-on method, respectively.

An evaluation sheet for green remodeling envelope systems that could utilize the constructed databases for environmental, economic, and energy performance was proposed.

The case analysis of the proposed evaluation sheet revealed that the proposed combinations of the insulation systems showed economic, energy, and environmental performances higher by 30%, 10%, and 30%, respectively, than those of the reference combination. Regarding the window systems, the economic and energy performances of the proposed input material combinations were higher than those of the reference combination by 22% and 10%, respectively. Furthermore, input material combinations with energy performance higher than the reference combination by 8% to 64% were proposed through the add-on window method.

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