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Establishment and analysis of evaluation criteria for green remodeling decision-making of small-scale private buildings

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ABSTRACT

To achieve the national net-zero goal, green remodeling of small-scale buildings, which make up the majority of structures, is essential. The green remodeling of South Korea is in the early stages of diffusion and is being conducted with government support, focusing on public buildings. The decision-making process for green remodeling centered on public projects relies heavily on experts and has the luxury of time and cost, making it unsuitable for small private buildings. We propose a priority evaluation system for the application of key technologies in the development of a decision support model for green remodeling projects amidst small-scale private buildings. Using an analytical hierarchy process, we created a layered set of evaluation criteria based on building performance, economic efficiency, and socio-environmental aspects, and determined their relative importance through a survey. The results revealed that economic factors have a greater influence than that by energy factors. This suggests that differences in perspective may exist between energy and non-energy experts with decision-making authority, such as building owners. This study is expected to contribute to the promotion of green remodeling by presenting alternatives that decision-makers can accept. Additionally, it is anticipated to serve as foundational data for policy formulation and support strategy development from the perspective of actual demand.

1. Introduction

South Korea considers the management and reduction of energy consumption and carbon emissions in the building sector as one of the key methods to achieve the net-zero goal by 2050 under the Paris Agreement. New buildings are expanding the scope of mandatory zero-energy buildings, and existing buildings, especially public ones, are being improved in energy performance through deep renovation [1]. From an institutional perspective, the zero-energy transformation of new buildings already reached a mature stage in South Korea. The envelope insulating performance of buildings constructed after 2018 already reached passive levels. According to government announcements, newly built apartments can save 23 % more energy compared with those completed 40 years ago [2]. However, according to 2022 statistical data [3], newly constructed buildings less than 10 years old account for only 16.7 % of the total number of buildings. A total of 41.0 % are existing buildings over 30 years old, built before energy standards were strengthened. Therefore, improving the energy performance of numerous existing aging buildings is critical to achieving net zero in the building sector.

Currently, the improvement of energy performance in existing buildings is in its early stages politically and is focused solely on public buildings owned by the state. However, public and privately owned buildings account for only 3.1 % and a much larger 77.6 % of all buildings, respectively [3]. Therefore, to achieve proper net zero, the improvement of energy performance in privately owned old buildings should be prioritized.

In South Korea, the implementation of improving the energy performance of such old buildings is called green remodeling. The institutional definition of green remodeling is “the activity of converting existing buildings into green buildings through energy performance improvement and efficiency enhancement” [4]. A green building refers to a “building comprising high energy efficiency and a high proportion of renewable energy use, while minimizing greenhouse gas emissions,” and “a building minimizing the impact on the environment and providing a comfortable and healthy living environment” [5,6]. Therefore, the green remodeling of South Korea encompasses both architectural and equipment improvements, aiming for a qualitative

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enhancement of the overall environment, including comfort and safety. It is similar to that of the internationally used terms such as 'deep renovation,' 'deep energy retrofit,' and 'green retrofit.'.

Green remodeling is currently being promoted primarily as a government policy project targeting aging public buildings rather than private ones. This project provides financial support for construction costs associated with implementing various technologies, including insulation work, the replacement of high-performance windows, high-efficiency heating and cooling systems, solar control devices, shading devices, ventilation systems, and solar power generation equipment [7]. To ensure the successful implementation of these financial investments, the government is engaging experts to provide energy consulting services for each building. The experts diagnose the existing performance of the building before the design and conduct a strategic review of each element using energy analysis programs. Furthermore, they assist architects in developing design plans improving the overall energy performance of buildings.

In the case of private buildings, limited budgets and scarce time make it very difficult to involve energy experts in every project, as is the case with public buildings. Furthermore, because extra costs are often incurred, most projects do not include separate energy consultants. Therefore, it is difficult to conduct green remodeling, and even after completion, it often relies on insufficient knowledge and experience of non-experts in energy, such as the building owner, architect, or contractor. These circumstances negatively affect energy efficiency due to incorrect design and inappropriate technology choices. To promote the green remodeling of private buildings, it is necessary to have decision-making systems and tools allowing even non-experts in energy to consider the characteristics of the buildings and make objective choices through comprehensive judgments of the applied technological elements.

Various studies discussing decision-making in the initial design phase of sustainable buildings comprise a higher potential for optimization in terms of building efficiency and cost [8]. Similarly, green remodeling is also a project considering both the sustainability and energy performance of buildings, making initial decision-making crucial for determining the overall direction of the project and increasing its chances of success. Among the representative methodologies for making rational decisions in the early stages are the Parametric Method and Multi-Criteria Decision Making (MCDM).

The parametric method sets parameters for architectural design and energy performance elements and suggests the optimal plan through effect analysis based on each variable. Primarily, objective variables such as energy performance elements (building form, envelope performance, building age, window-to-wall ratio, etc.) and cost are often adopted [9–11]. Hence, the process is very complex as simulation programs are often used to compare each design alternative. Therefore, to some degree, it is impractical to choose it as a methodology for quick decision-making by non-experts.

MCDM is a decision-making methodology considering various criteria together to make the optimal decision among multiple alternatives, and it is the most widely used decision-making method in various fields such as energy and environment, industry, economy, and production [12]. The advantage of this method is that it allows for a more comprehensive and balanced decision-making process by comprehensively analyzing multiple evaluation criteria to select the optimal alternative for complex problems. Among the various types of MCDM, the most commonly used is Analytic Hierarchy Process (AHP), which is a method for deriving the optimal solution through systematic pairwise comparisons in complex decision-making situations. This method allows for the quantification of subjective judgment criteria for decision-making and ensures reliability through consistency review.

However, the disadvantage of AHP is that as the number of evaluation criteria increases, respondent fatigue also increases, and results may vary depending on their knowledge level or biases. To mitigate these limitations and ensure reliability, providing an objective and comprehensive explanation for each item in advance is crucial. Despite its limitations, AHP is particularly effective for establishing verifiable weights in the initial stages of decision-making. Its modeling and data requirements are less stringent than those of parametric methods, making it a highly efficient tool for narrowing down alternatives under the typical resource constraints of early-stage planning.

We propose an evaluation system for quantitatively analyzing the importance and priority of green remodeling element technologies as a preliminary research phase for developing a decision-making tool for green remodeling by utilizing AHP. In this process, most of the decisions are based on the opinions of experts. Hence, decision-making in green remodeling often relies on the knowledge and experience of stakeholders with limited understanding of building structures and the energy performance of applicable technologies (e.g., owners, architects, and contractors). This reliance can lead to suboptimal design and technology choices, degrading whole-building energy performance relative to that of baseline conditions and widening the gap between predicted and actual outcomes. In practice—particularly for small-scale projects—non-technical considerations, such as construction costs and schedules, frequently exert a greater influence than those by the performance metrics on the selection of green remodeling measures. Accordingly, incorporating the priorities of non-experts into the development of decision-support tools is essential to enhance their practical utility and uptake.

We present the relative importance of each element technology and the policy and practical implications based on these analytical results. This study is significant because it reveals the factors important to decision-makers, such as building owners with limited energy-related knowledge, in the early stages of design. This information could contribute to the development of highly useful decision-making support tools in the future. Through follow-up research, it was assumed that any aspects of energy performance that could be compromised by not reflecting on expert opinions would be supplemented by using the existing database of green remodeling best practices, which ensures a certain level of performance, or by conducting an additional expert survey. Additionally, this study is characterized by the development of a decision-making tool specifically tailored for small-scale building projects, which is often not employed by green remodeling and energy consulting experts due to cost and time constraints. This tool is expected to positively impact the future revitalization of green remodeling by enabling property owners to select effective technological components enhancing the performance of aging buildings while aligning with those of their individual preferences.

2. Theoretical background and literature review

We utilized AHP to derive the priorities for green remodeling. AHP is a widely used methodology for decision-making because it can systematize and quantify complex decision-making processes. Especially in the field of architecture, decision-making is significantly influenced not only by objective facts but also by the subjective judgments of decision-makers such as clients or architects, based on their economic, social, and environmental circumstances. Therefore, many studies in the field of architecture adopt this method.

Lhee [13] utilized this method to analyze the importance of each construction sector in the green remodeling project of the school. However, in proposing the technical elements that should be prioritized, the evaluation criteria are limited to the construction sections and elements. It provides the relative importance of each element related to architecture, machinery, lighting, and renewable energy; however, it is limited to energy performance and lacks consideration for economic feasibility and constructability. Serrano-Jiménez [14] proposed a decision support model for remodeling old houses, reflecting a wider range of decision-making factors. Through evaluation criteria such as construction period, scale, technical complexity, and energy savings, it allows the client or architect to choose the intensity level of the remodeling. Similarly, various studies presented different evaluation criteria considering environmental, social, and economic aspects as decision-making criteria and determined the weights used to prioritize each technical element [15–17]. Therefore, we also aimed to support decision-making in the initial design phase by systematizing the evaluation criteria for green remodeling element technologies using AHP and deriving their relative importance.

Therefore, we reviewed the criteria selected through a prior study on improving the performance of aging buildings or sustainability. The criteria for decision assessment in related research papers is summarized in Table 1. Son [18] examined the relative importance of economic factors and residential environment considerations, such as design and regulatory compliance. As it mainly focused on the demolition and reconstruction of large buildings, its direct relevance to small-scale green remodeling—the main focus of this work—is limited; however, it confirms that economic considerations hold significant decision-making influence. Olsson [19] and Li [21] emphasize carbon emissions from a life-cycle perspective, accounting not only for operational energy use but also for embodied carbon. Given that the aims of green remodeling include both upgrading aging buildings and contributing to carbon neutrality, such life-cycle carbon metrics are essential. Li [20] further extends the scope beyond energy and economics to include social conditions—such as usability, safety, and aesthetics—and indoor environmental quality (e.g., acoustics and lighting). While this breadth facilitates more holistic decision-making, attributes like aesthetics can be subject to considerable individual variability; thus, for more streamlined decision processes, it may be advisable to narrow the set of criteria to those permitting objective assessment. Amorocho [15] incorporates renovation time within a decision tree. As occupants of small existing buildings typically wish to avoid prolonged vacancy during green remodeling, construction duration is likewise a criterion warranting explicit consideration. Caruso [25] focused on addressing environmental, economic, and social issues from a holistic perspective, based on a life cycle thinking approach. They also considered environmental payback periods in addition to economic budgets, operational periods, and economic investment periods. Discussions from a life cycle perspective are deemed necessary in decision-making.

Commonly, they included aspects of energy performance, carbon emission performance, and economic feasibility. Here, energy performance is evaluated in terms of the final energy consumption used in the building, and carbon emission performance is assessed by evaluating the total carbon emissions of the building converted using carbon emission coefficients and the resulting environmental impact. Energy performance and carbon emissions are very closely related, and hence, they can be grouped together in terms of building performance. Economic feasibility includes the overall aspects such as initial investment costs, maintenance and operation costs, payback period, and increase in property value. Additionally, social and environmental factors (e.g., the preservation of the building structure, reduction of construction period, noise), residential environment, and indoor thermal comfort were also considered [15,16,18–24].

In most earlier studies, the weights for evaluation criteria used to derive the optimal alternative were based on expert value judgments. The opinion of experts is important, as it significantly impacts the energy performance of buildings. However, providing many expert-centered options makes it difficult for non-experts to utilize them in their then current state.

In small private projects, decisions regarding capital expenditure approval and the necessity and duration of temporary relocation caused by construction typically depend on non-experts, such as owners and users. These preferences directly influence the scope of construction and the selection of technological elements during the initial planning phase of green remodeling. Therefore, it is essential to present intuitive, concise alternatives alongside a weighting calculation derived from their value judgments. Fundamentally, the criteria for value judgment are assessed within the framework of basic regulations considered by many experts to be minimum prerequisites. By establishing the minimum conditions mandated by law as mandatory constraints, the irrational choices made by non-experts can be effectively mitigated. This will increase the likelihood of green remodeling element technologies being applied in practice and enhance the perceived effect through value-based decision-making. The study direction can be used as basic data necessary for the establishment of policies or the formulation of support strategies from the perspective of actual demand in the future.

3. Methods

We applied the AHP method to analyze the relative importance of green remodeling element technologies. AHP is an analytical tool quantitatively resolving complex decision-making problems by decomposing evaluation subjects into a hierarchical structure and quantifying the importance of each element through pairwise comparisons. Here, the following procedures were performed: (1) deriving evaluation factors and establishing a hierarchical structure, (2) designing and collecting surveys, (3) conducting pairwise comparisons and determining weights, and (4) reviewing consistency and deriving analysis results.

First, the applicable element technologies to be reflected in the early stages of green remodeling design utilized the classification system based on government public support projects, as shown in Table 2 [26]. Each element technology is designated by the government in green remodeling guidelines for aging public buildings and consists of factors influencing energy performance and indoor comfort improvement. These element technologies are improved and parts with deteriorating performance were replaced through an investigation of the aging characteristics of the target building. According to the project guidelines [27], the level of thermal performance improvement for the building

Table 1
Criteria for consideration in remodeling-related decision making.

Related Research	Decision-Making Criteria				
	Energy Performance	Carbon Emissions (Environmental Impact)	Economic Feasibility	Socio-environmental Factors	Others
Son, You, Lee & Choi [18]			○		Design, Residential Environment
Olsson, Malmqvist & Glaumann [19]	○	○	○		
Li & Froese [20]	○		○	○	Acoustic, Lighting, and IAQ
Li, Ng & Skitmore [21]	○	○			
Chang, Castro-Lacouture & Yamagata [22]	○	○	○		Thermal Comfort
Pinzon Amorocho & Hartmann [15]	○	○	○	○	
Yuan Shi, et al. [16]	○	○	○		Thermal Comfort
Golić, Kosić & Kosorić [23]	○	○	○		
Caruso, et al. [25]	○	○	○	○	

Table 2
Performance improvement levels by support item of the public building green remodeling support project.

Category	Subcategory	Relevant Standards & Product Certifications	Performance Improvement Criteria
Architecture	Thermal insulation	Based on 'The Building Energy Saving Design Standards' and its 'Regional Heat Transfer Coefficient Standards'	Seoul region, exterior thermal transmittance criteria: – Wall: 0.24 $W/m^2 \cdot K$ or less – Roof: 0.15 $W/m^2 \cdot K$ or less – Floor: 0.17 $W/m^2 \cdot K$ or less
	High-performance windows and doors		Seoul region: – 1.5 $W/m^2 \cdot K$ or less – Recommendation of Low-E double glazing windows and insulated doors
(High-efficiency) Mechanical & Electrical	Heat recovery ventilation systems(HRV)	Products certified under KS B 6879 standards	Effective Exchange Efficiency: – Heating: $\geq$ 70 % – Cooling: $\geq$ 45 %
	Heating & cooling equipment	Certified as high-efficiency energy equipment or achieving Energy Efficiency Grade 1	– Heating: COP 4.10 or higher – Cooling: COP 3.90 or higher
	Boilers		– Gas boiler: 91 % or higher
	LED Lights		Lighting power density (W/m^2) $\leq$ 14
	Photovoltaic	Based on 'Guidelines on support for renewable energy systems'	Module efficiency: 18 % or higher

structure must exceed the performance of the latest 'Building Energy Saving Design Standards.' Additionally, for equipment, it is required to use products that obtained the high-efficiency energy equipment certification designated by the Korean government or achieved an energy consumption efficiency grade of 1.

The evaluation criteria for prioritizing the application of specific technologies in the remodeling of small-scale private buildings were established through the analysis of existing literature and prior research. The evaluation criteria identified in most earlier studies can be broadly reclassified into building performance, economic feasibility, and social aspects based on their characteristics and similarities. Energy and carbon emission performance are closely related, and hence, they were grouped together under building performance. Here, the evaluation criteria were hierarchically categorized into Levels 1 and 2, as shown in Fig. 1.

First, the architectural performance aspect includes items related to performance from the application of each element technology. The subcategories of this item consist of energy savings in buildings, reduction of carbon emissions, and reduction of negative environmental impacts. This is one of the most important elements in green remodeling, and was selected by presenting direct and quantitative goals. Building energy savings refer to the final energy used in a building, which implies the level at which the occupants can directly observe a reduction in their usage.

The reduction of carbon emissions is a concept considering the environmental load generated from the production stage of the energy sources I use (electricity, gas, etc.), implying a reduction in the global load. Generally, energy savings in buildings lead to a reduction in carbon emissions, although it was explained that the extent of this reduction can vary depending on the type of energy source used, and the importance of this was evaluated. For example, even if a building has boilers with the same energy-saving performance, the carbon emissions can differ depending on whether they are electric or gas boilers. Specifically, this standard aligns with current carbon neutrality policies and distinguishes itself from simple energy conservation. However, this concept remains ambiguous for general consumers. Therefore, during the survey, these aspects were explained and distinguished to evaluate their importance.

Reducing negative impacts on the environment implies reducing aspects that can broadly harm the environment, in addition to carbon emissions. For example, it implies to improving air quality by not using materials emitting harmful substances such as asbestos, formaldehyde, and volatile organic compounds, which deteriorate indoor air quality, or using water-saving products to conserve water. This is an essential part of assessing sustainability beyond energy and carbon, and is a key issue in improving the quality of life for residents.

Second, from an economic perspective, the detailed items were categorized into three: initial investment cost, payback period, and increase in rent or property value. Initial investment costs refer to all costs associated with a green remodeling project. Unlike public works projects, small-scale construction projects face significant budget constraints, making this a crucial factor in initial decision-making. The payback period refers to the duration for the energy cost savings from the green remodeling to offset the initial investment cost. The increase in rent or building value refers to the economic benefits resulting from the improved energy and environmental performance of the building through green remodeling. They are crucial in economic evaluation as criteria for judging the rationality and future profitability of an investment.

Third, from a socio-environmental perspective, the construction period was set as a detailed item. In the case of green remodeling projects for small-scale buildings, it is often difficult to leave the building vacant for an extended period because it has been used continuously for an extended period. Accordingly, many cases exist where the project is undertaken while the building is still occupied. Additionally, as the construction period increases, the risk of safety accidents and environmental pollution caused by the construction can also increase[28]. Therefore, the construction period can also be considered as one of the important factors in decision-making. In the literature review, various factors such as noise, indoor comfort, and civil complaints were considered; however, these elements were excluded due to their ambiguity in quantifying indicators. Conversely, a calculation standard exists for determining the standard construction period, allowing for quantification. Furthermore, risks associated with noise and civil safety are closely linked to the construction period, leading to their exclusion to simplify the AHP model and reduce response fatigue.

The relative preference for evaluation criteria was structured in a questionnaire to allow for pairwise comparisons, and the questionnaire used a 9-point scale commonly employed in AHP. This scale is designed so that equally important items are given a midpoint score of 1, and items of greater and lower importance are given maximum scores of $+5$ and -5, respectively. Negative values are replaced with their reciprocals. The survey response results are used to create a pairwise comparison matrix, and pairwise comparisons are conducted for 'n' evaluation items. The geometric mean of each matrix is calculated and normalized to determine the relative importance (weights). This process converts qualitative judgments between each element technology into quantitative ratios.

The relative importance derived accordingly undergoes a process of reliability assessment through consistency verification once again. The consistency is assessed by the Consistency Index (C.I.). When this value is 0.1 or lower, it indicates that the analysis results are reliable. C.I. can be calculated as shown in Eq. (1), where λ, λ_{max}, and n are the consistency ratio, the average of the sum of consistency ratios, and the number of alternatives, respectively. The Consistency Ratio (C.R.) is given by Eq. (2), where the Random Consistency Index (RCI) is defined according to the number of alternatives n as shown in Table 3.

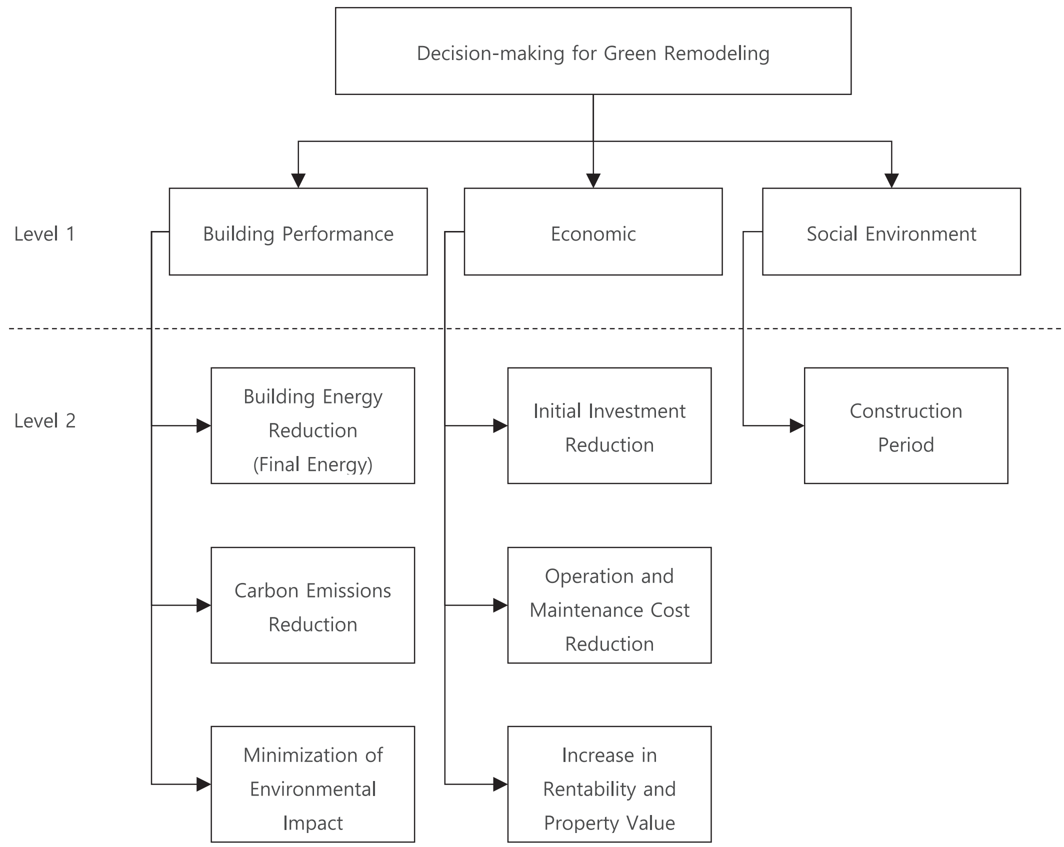

Fig. 1. Hierarchical structure of evaluation criteria for green remodeling decision-making.

Table 3
Random Consistency Index (RCI).

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

$$\text{C.I.} = (\lambda_{max} - n) / (n - 1) \tag{1}$$

$$\text{C.R} = \text{C.I.} / \text{RCI} \tag{2}$$

C.R.(λ) can be calculated using Eqs. (3) and (4). Once the consistency review is completed, the final weights for each evaluation criterion are determined.

$$\text{Consistency Ratio}\,(\lambda) = \text{Weight product} / \text{Weight} \tag{3}$$

$$\text{Weight product} = \begin{bmatrix} a_{11}a_{12}a_{13} \\ a_{21}a_{22}a_{23} \\ a_{31}a_{32}a_{33} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} a_{11}w_1 + a_{12}w_2 + a_{13}w_3 \\ a_{21}w_1 + a_{22}w_2 + a_{23}w_3 \\ a_{31}w_1 + a_{32}w_2 + a_{33}w_3 \end{bmatrix} \tag{4}$$

The target of the survey was the general public aged 30–50 who are likely to undertake actual remodeling projects. According to statistics of South Korea on housing ownership by age, the 30 s, 40 s, and 50 s accounts for 9.5 %, 21.2 %, and 25.2 %, respectively, collectively represent over half of all ownership [29]. Thus, people in their 30 s to 50 s constitute the core age group of homeowners. Furthermore, as they are economically active and possess actual decision-making authority for investments, they are also the age group most likely to express proactive intentions toward energy cost reduction and residential environment improvement. Therefore, this group was selected as the target respondents for the survey. The survey was conducted over a period of 15 days, from October 1 to 15, 2024, and a total of 71 survey responses were collected. Among these, 69 valid responses were used for analysis, excluding 2 invalid ones. Data analysis was conducted using two analysis programs: Microsoft Excel and IBM SPSS Statistics 26. The completed responses were used to calculate weights through pairwise comparisons for each evaluation criterion, and accordingly, the priorities of suitable element technologies for improving building energy performance were proposed.

A case study was conducted on small-scale buildings to verify and utilize the proposed priorities. The building used for the analysis is shown in Table 4. It is a daycare center located in Seoul, completed in 1993, and has been in use for over 30 years. The total floor area of the building is 378.18 m^3, making it a small single building consisting of one basement level and three above-ground levels. Through consultations with the architect, it was possible to analyze the energy performance of the existing buildings by securing their blueprints and performance information. Relatively accurate cost estimates for each element of the technology could be obtained by securing a simplified breakdown of the construction costs.

To determine priorities, an analysis based on evaluation criteria such as energy consumption, carbon emissions, and initial investment costs for the element technology of each building must be conducted first. In the case of analyzing the energy savings and carbon emissions of

Table 4
Building information.

Category	Details	Category	Details
Year Built	1993	Location	Seoul, South Korea
Floor Level	B1 / 3F	Building Type	Daycare Center
Total Floor Area	378.18 m^2	Structure	Reinforced Concrete
Building Area	105.12 m^2	Exterior Wall	Exterior Insulation + Composite Wood

buildings, the certification energy evaluation program of the Korean government, ECO2-OD, was used, which introduced evaluation methods according to international standards such as ISO 13790 and DIN 18599, and it evaluates energy consumption through a monthly analysis method based on quasi-steady-state interpretation [30].

The evaluation of the hierarchical structure here was based on government guidelines, actual cost databases, and simulation data. Energy savings should be perceived at the consumer level, and hence, they were calculated based on secondary energy savings rather than those of the primary. We used the simulation value for that of the result. The carbon emissions value was converted from the reduction amount based on the reduction. In this case, the carbon emissions during the production stage of the materials were not considered. As for the reduction of environmental impact, an evaluation should be conducted to determine whether it negatively affects the atmosphere and indoor air quality, among other factors. However, as most of the materials used in this case are eco-friendly, the same values were applied.

The initial investment cost in the economic feasibility section was based on the preliminary estimate of applying the relevant technology to the actual target building. The estimated price was based on actual estimates received for the actual green remodeling project of the target building. While the costs here were estimated using quotes from a specific project, future studies could employ the standard material unit price list of the government to ensure greater consistency and generalizability. Cost savings from maintenance and management ultimately refer to the economic benefits obtained from reduced energy costs, and hence, the annual energy savings were converted into costs, and the payback period for the initial investment was evaluated. Specifically, maintenance costs can be calculated by multiplying the annual energy savings by the unit price. The payback period was evaluated using the Net Present Value (NPV) and the Internal Rate of Return (IRR). In the case of an increase in building value, obtaining objective data is difficult. Accordingly, a rule-based ordinal scale (High/Medium/Low) was assigned and sensitivity analysis was conducted. For example, high scores were given to element technologies visibly confirming the improvement of the building through changes in interior design and exterior materials, while lower scores were given to those that could not be verified, such as equipment and facilities. In the future, additional research on the increase in building value will be necessary. Lastly, regarding the construction period, the architectural construction reference was based on the guidelines by the government for estimating the construction period of public buildings [31], while the equipment construction reference was based on the opinions of experts from related companies.

Accordingly, the results analyzed by item were re-evaluated on a 10-point scale through a normalization process, as shown in Eq. (5). Here, X is the performance review result of each element technology, and Min (X) and Max(X) are the minimum and maximum values of X, respectively. Eqs. (5) and (6) are preferable when the values are larger and smaller, respectively. N is the value converted to a score out of 10. Here, the final score was determined by summing the products of the N values for each section multiplied by the weight w, as shown in Eq. (6). The higher the calculated score, the more important the element technology is, and priorities can be determined based on this.

$$N_i = \left(\frac{X_i - \min(X)}{max(X) - \min(X)}\right)*(10-1)+1 \tag{5}$$

$$N_i = \left(\frac{\max(X) - X_i}{max(X) - \min(X)}\right)*(10-1)+1 \tag{6}$$

$$\text{Score } = \sum\nolimits_{i=1}^{n}(N_i*w_i) \tag{7}$$

4. Results

4.1. Survey and analysis results

The results of the importance analysis through the survey analysis are shown in Table 5. According to the importance assessment results for the first Level 1, the ranking was as follows: economic feasibility > building performance > social environment. The ranking of importance of the detailed items in terms of Level 2 building performance was as follows: building energy reduction > environmental impact reduction > carbon emission reduction. It appears that most respondents place greater importance on items that can be tangibly felt, such as building energy savings. The importance of each aspect of economic feasibility was ranked as follows: reduction in maintenance costs > increase in building value > reduction in initial investment costs. Similar to those of the building performance, they considered the tangible reduction in maintenance costs to be more important and showed a high interest in the potential value increase through green remodeling of the building.

The final importance is determined by multiplying the Levels 1 and 2 values for each criterion within the group. Higher values indicate greater value. All C.R. values were confirmed to be less than 0.1. The priority order of the seven value judgment criteria was as follows: construction period > building energy reduction > maintenance cost reduction > building value increase > initial investment cost reduction > environmental impact reduction > carbon emission reduction. The performance and economic efficiency of the building are important, although as it is a remodeling project of an existing building, the importance of the construction period appears relatively larger. The construction period can be considered closely related to the scope and cost of the project. Additionally, the importance of factors that can confirm the tangible effects of the construction, such as building energy savings or economic aspects, were found to be high.

Consequently, it was found that items directly or indirectly related to economic feasibility significantly impact decision-making. Thus, an investigation was conducted to determine the level of additional costs that could be tolerated when performing green remodeling compared with those in regular construction. The result showed that even if additional construction costs exceeding a certain amount were incurred, they could be tolerated, as shown in Fig. 2. The ratio of respondents who answered that the additional construction cost could rise by up to 20 % was the highest at 36.2 %, followed by 30 % at 27.5 %, and 10 % at 18.8 %. As shown in Fig. 3, respondents indicated that they hope to recover their initial investment quickly, which was proportional to the amount of cost invested. Less than 5 and 3 years accounted for 40.6 % and 37.7 %, respectively, representing a high proportion.

Table 5
Final weight calculation results by evaluation criteria.

Level 1		Level 2		Final Weight	
Building Performance	0.389	Building Energy Reduction(X1)	0.460	0.188	2nd Priority
		Carbon Emissions Reduction(X2)	0.260	0.102	7th Priority
		Minimization of Environmental Impact (X3)	0.280	0.107	6th Priority
Economic	0.414	Initial Investment Reduction(X4)	0.293	0.128	5th Priority
		Operation and Maintenance Cost Reduction(X5)	0.357	0.141	3rd Priority
		Increase in Rentability and Property Value(X6)	0.350	0.136	4th Priority
Social Environment	0.197	Construction Period (X7)	1.000	0.198	1st Priority
Sum (C.R. ≤ 0.1)				1.000	

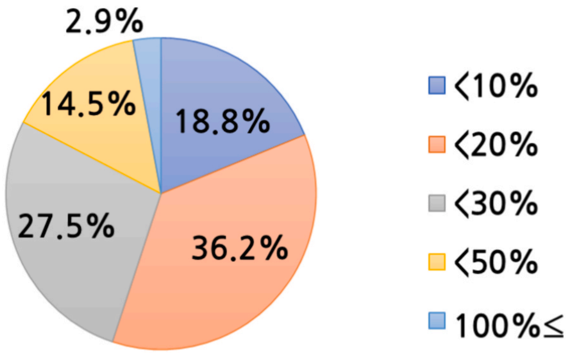

Fig. 2. Amount that can be additionally covered compared with that of standard remodeling.

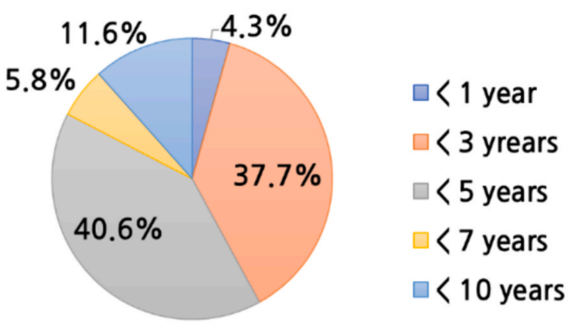

Fig. 3. Desired initial investment payback period.

Based on the results of this survey, respondents appear to pursue high energy efficiency in buildings and approve of an increase in investment costs to a certain extent. Instead, the construction and payback periods for the initial investment should be short, to reduced maintenance and operating costs.

4.2. Case study

Generally, in small-scale private buildings, unlike public or large-scale projects, it is difficult to reflect and improve all the requirements needed for green remodeling due to cost constraints. We derived the weights for the criteria of value judgment necessary for efficient green remodeling, aimed at decision-makers such as building owners or architects. Using this data, a case study was conducted on small-scale buildings.

The results of the field survey for the target building are presented in Fig. 4. Some parts of the exterior and interior walls of the building were found to have cracks or leaks, and concerns existed that the airtightness of some extended sections, windows, and doors may be compromised. Additionally, it was determined that enhancing the insulation and airtightness of the building envelope is necessary. Furthermore, replacement was necessary because the heating and cooling equipment was over 10 years old, resulting in significantly lower energy efficiency compared with that of the current standards.

The green remodeling plan recommends considering ventilation systems that can improve indoor air quality and solar power systems for eco-friendly energy production, in addition to improving and replacing existing structures and equipment. In the case of the target building, local government policy recommends installing ventilation systems recovering heat in daycare centers following the COVID-19 pandemic. Therefore, this was considered during the green remodeling plan. Additionally, the east-facing facade of the building comprises conditions allowing for sufficient solar radiation to be captured for solar power generation. Therefore, the building-integrated photovoltaic (BIPV) system was also considered to ensure access to clean energy resources.

Consequently, this case study identified five green remodeling element technologies needed to be reviewed in advance to improve building performance: insulation, windows and doors, heating and cooling, heat recovery ventilation systems, and solar power generation. Before determining the priority of each element, a performance survey was conducted for each area before improvement, and the required levels were presented in Table 6, considering the recent legal standards.

Based on the survey results, the importance of each element technology was evaluated. The evaluation criteria were energy savings in buildings (X1), reduction of carbon emissions (X2), reduction of environmental impact (X3), reduction of initial investment costs (X4), reduction of maintenance costs (X5), increase in building value (X6), and construction period (X7). The evaluation results of these criteria were summed up to determine the priorities.

First, the item-by-item analysis results for the element technologies requiring improvement are shown in Fig. 5. Among the elements of green remodeling, the replacement of the heating and cooling system was rated the highest priority with a score of 7.5. The second priority

Fig. 4. Photos of the field survey of the target building.

Table 6
Comparison of building performance before and after improvements.

Element	Existing Performance	Target Performance
Insulation	Thermal transmittance (U-value): −Wall: 0.58 W/m^2·K −Roof: 0.41 W/m^2·K	Thermal transmittance (U-value): −Wall: 0.24 W/m^2·K −Roof: 0.15 W/m^2·K
Windows	U-value: 2.1 W/m^2·K	U-value: 1.5 W/m^2·K
Heating & Cooling	−Electric Heat Pump: 37.9 kW, COP 3.3 −Boiler: 116 kW, efficiency 83 %	−Electric Heat Pump: 50.3 kW, COP 4.3
HRV	–	Effective Exchange Efficiency: – Heating: ≥ 70 % – Cooling: ≥ 60 %
Photovoltaic	–	4.9 kW BIPV (East side)

was the installation of a heat recovery ventilation system, the third was a renewable energy system, the fourth was insulation, and the fifth was window replacement. The first to third priorities were all active systems, which had much shorter construction periods compared with those of passive systems, securing high scores. Especially in the case of insulation, the construction period was much longer compared with that of other element technologies, which is the reason for not being preferred by the clients. Specifically, if only one element technology was applied due to budget constraints, a higher preference for active systems existed. These results are in contrast to those of the prioritizing passive systems, particularly the improvement of insulation materials, in terms of energy savings and carbon emission reduction [32] when making decisions about green remodeling and performing existing deep renovations.

In the case of insulation work, as can be inferred from the survey results, it may be perceived as a difficult task from the perspective of building owners who are actually performing green remodeling, due to the short construction period and investment cost aspects. However, from the perspective of building energy and net zero, improving insulation performance is a very important issue. The insulation requirements specified in the energy design standards of the government can be regarded as expert-endorsed minimum criteria. Accordingly, we fix the code-mandated insulation level as a binding prerequisite and re-evaluate the priorities of the remaining alternatives satisfying this constraint. Consequently, as shown in Fig. 6, the improvement of the heat exchange ventilation system was prioritized higher than that of the replacement of the heating and cooling equipment. It appears that when insulation is fundamentally installed, the energy savings achieved at a certain level make the heat exchange ventilation system highly valued, which is cheaper than that of the other heating and cooling equipment in terms of cost.

5. Discussion

Our results differ somewhat from the passive-first strategy emphasized in the deep renovation literature. Most prior studies emphasize the importance of envelope performance for long-term energy and carbon savings. But, based on the analysis result, respondents tended to prioritize economic feasibility over building performance. Specifically, they placed a high value on criteria such as the cost of glass management and the potential increase in building value. When the detailed evaluation criteria were examined, a high level of interest existed in energy savings for the building, where energy refers to the final energy that users can directly experience through energy bills and other means.

Using the example of small-scale buildings, the application of these

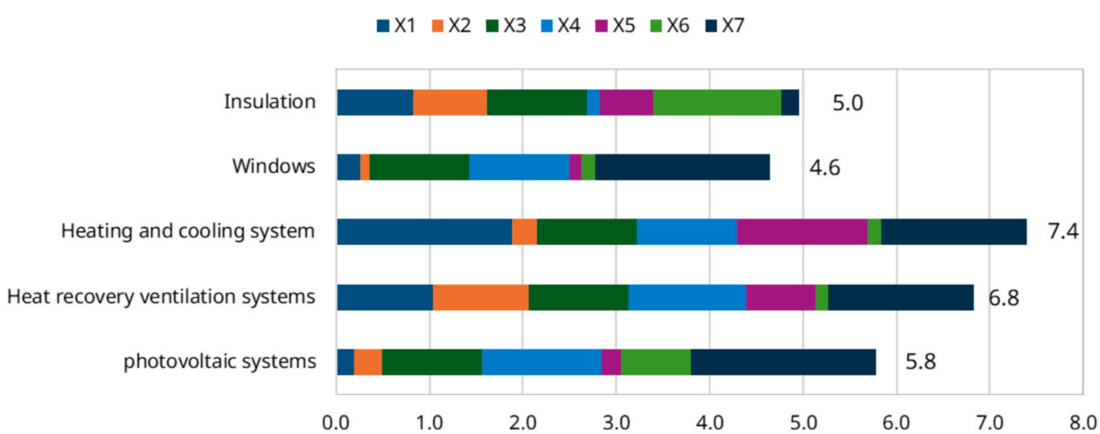

Fig. 5. Analysis result of the priority ranking of green remodeling element technologies.

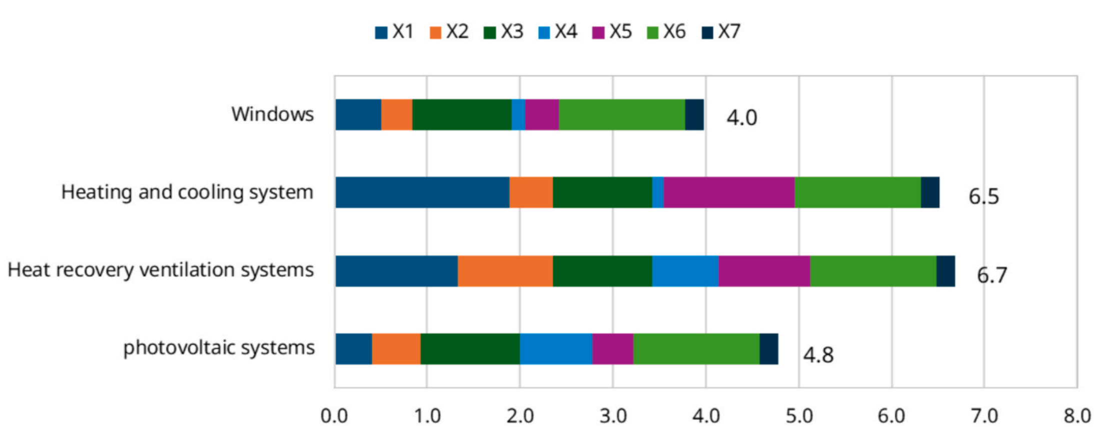

Fig. 6. Improvement of insulation performance + prioritization of additional elements.

criteria corresponded to the fact that, despite the significant energy-saving effect of passive technologies like insulation reinforcement, they were given lower priority due to the burden of construction period and initial costs. Active technologies with short construction periods and clear perceptible effects, such as the replacement of heating and cooling systems or the introduction of heat recovery ventilation systems, were given high priorities. In cases where insulation was assumed, the introduction of a heat recovery ventilation system was prioritized over the replacement of the heating and cooling system. This is because it is considered less taxing in terms of construction costs if a certain level of energy savings is secured. Given that the budget and time of an owner are the key determinants for small-scale building projects, in contrast to those of the large public, the most logical strategy for early-stage decision-making is to set regulatory minimums as a baseline. Within this framework, alternatives providing the greatest perceived savings in construction duration and operational costs should be presented first.

Therefore, we propose and verify a method to alleviate the problem of potential choices determined by non-expert preferences by setting the minimum requirements of energy-saving design standards as essential constraints. The finding that a prominent gap exists between the passive-first strategy and the investment preferences of actual users is particularly significant. This discussion is significant as it presents points to consider when designing future government subsidies or loan systems.

However, to ensure that the decision-making model leads to actual net-zero outcomes, it is necessary to incorporate additional expert opinions to refine the evaluation metrics beyond non-expert preferences. Additionally, in the case study, the life cycle assessment (LCA), including the material production and transportation stages for carbon emission calculation, was excluded, and an in-depth discussion on the value increase effect of the building could not be conducted. While the components of the economic evaluation were categorized by expenditure timing—initial investment, maintenance costs, and future asset value—to prevent overlap, a concern about double-counting persists. Therefore, future research should present methodologies for data extraction and incorporate the opinions of a diverse range of experts, such as architects, energy specialists, and builders, to address the limitations of the models to be developed.

6. Conclusions

One of the major challenges to achieving carbon neutrality in South Korea is how to efficiently improve the energy performance of small, aging private buildings, which constitute the majority of the building stock. However, green remodeling initiatives for this remain in their early stages, with efforts largely centered on the public sector. Accordingly, it is now necessary to explore strategies for broadening their application to the private sector.

Our main results showed that the importance of economic feasibility and construction period was significantly higher than those of other evaluation items, which confirmed that active technology tends to be adopted preferentially over passive technology. The traditional method, based on element technologies proposed by experts, focused on improving energy performance, and fully convincing non-expert clients is difficult due to resistance to construction costs. This study presents a practical decision-making support tool by systematically reflecting the value judgments of actual clients and users, moving away from the traditional expert-centered evaluation.

Therefore, we propose an effective decision-making model by incorporating the minimum requirements of energy-saving design standards into expert-based constraints and applying weights based on non-expert value judgments. This integrated model prevents irrational choices, guarantees a minimum level of energy quality, and presents satisfactory alternatives to building owners. This study is significant because it offers a theoretical basis for creating a decision-making model for green remodeling in small-scale buildings, while also illustrating its uses in real situations, providing basic information for future model development. Specifically, it is expected to increase the feasibility of the project and encourage voluntary investment.

Future supplementary research will enhance the reliability of the model by incorporating additional expert inputs to address decision-making bias. Furthermore, research is needed on design-related and on policy-related measures such as differential subsidies to shorten construction periods and for passive construction, respectively.

CRediT authorship contribution statement

Seong Eun Kim: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Yong Woo Song:** Writing – review & editing, Validation, Methodology. **Min Hee Chung:** Writing – review & editing, Methodology. **Jin Woo Moon:** Writing – review & editing, Funding acquisition. **Jin Chul Park:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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