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Prioritizing Energy Performance Improvement Factors for Senior Centers Based on Building Energy Simulation and Economic Feasibility

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Abstract: This study examined energy performance improvement factors by analyzing both energy performance and the economic impacts to reduce energy costs for senior centers. A fact-finding survey was conducted on 20 senior centers in a metropolitan area, identifying key energy improvement factors. Energy simulations of the buildings were performed using ECO2, an officially certified energy assessment program in Korea, comparing the energy requirements before and after the improvements. The energy demand, energy consumption, and floor area were analyzed, with the J, K, and S standard models selected based on the median values of these factors. To assess the impact of the improvements, blower door tests were conducted on two senior centers before and after window upgrades. Based on the ECO2 simulations and the blower door test results, improvement priorities were identified in the following order: windows, exterior walls, boilers, roofs, and doors. Finally, an economic feasibility analysis applied the construction and heating costs to the standard models. Over a 40-year period, only boiler improvements generated a net profit. Without government support, this study recommends prioritizing boiler upgrades when selecting energy performance improvements.

Keywords: senior center; building energy simulation; primary energy; life cycle cost; blower door test

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1. Introduction

Amid the global phenomena of climate change and abnormal warming, energy demand for buildings has been increasing. Following the rise in international oil prices due to the Russia–Ukraine war, issues regarding energy vulnerability among low-income groups have emerged in South Korea [1,2].

In addition, international oil prices have increased due to the Russia–Ukraine war, and in Korea, the issues of energy-vulnerable groups emerged due to the burden of heating energy costs [1,2]. The number of patients affected by hypothermia and frostbite, particularly elderly patients in their 60s and older, increased compared to 2021 due to the cost burden of heating energy consumption and abnormal temperature phenomena [3,4].

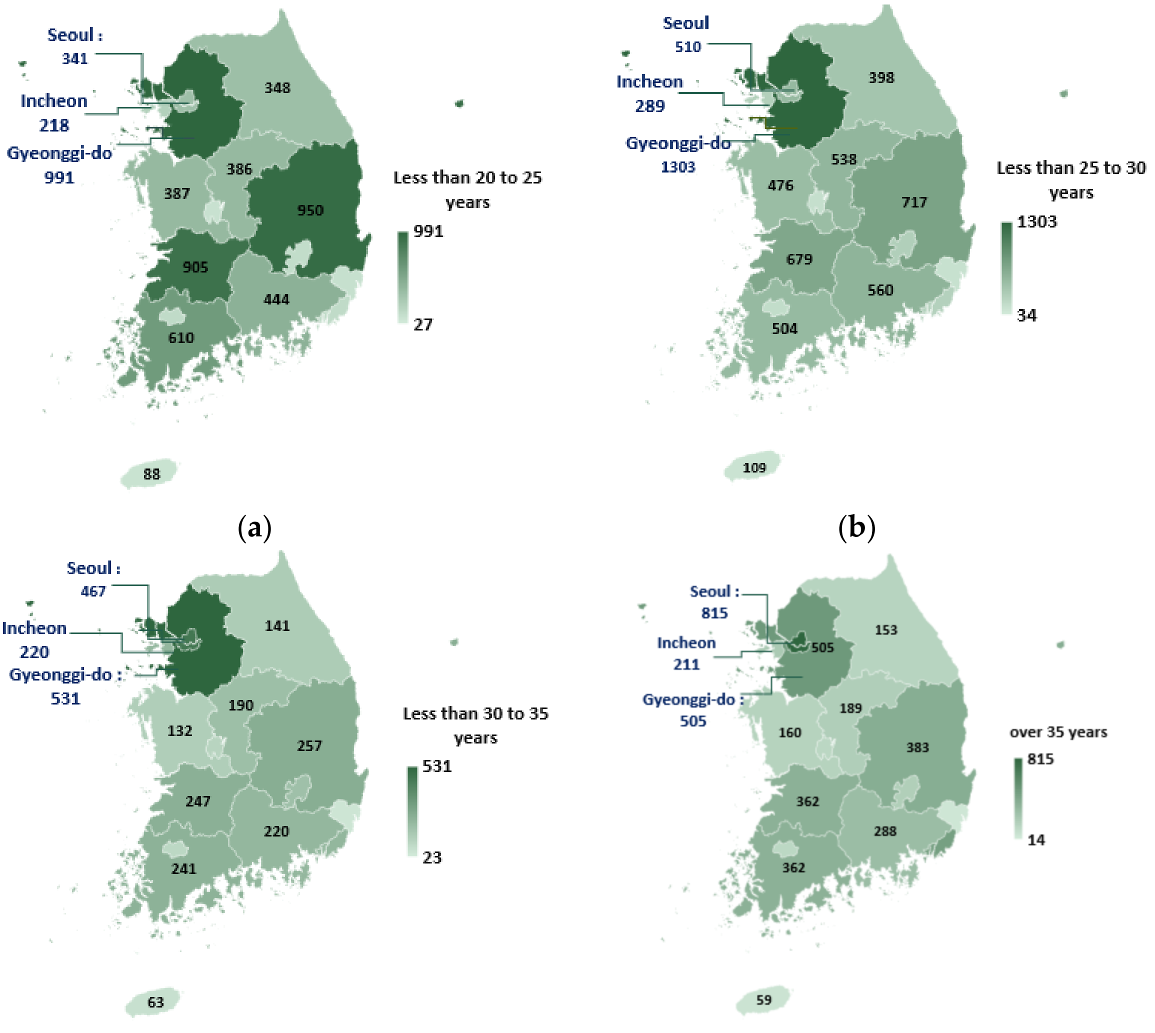
Senior centers, which are spaces for the elderly (over the age of 60), are often established in renovated buildings. Old senior centers have high air infiltration due to leakage areas in the building, which increases the heating load and increases energy consumption.

In order to achieve energy welfare for vulnerable groups through the improvement of energy performance in senior centers, the Seoul City implemented energy performance improvement projects at 15 locations in 2020, 7 locations in 2021, and 12 locations in 2022. This initiative also contributed to the reduction of greenhouse gas emissions from buildings by encouraging private sector participation. By prioritizing energy performance improvements when specifying the scope of renovations, the effectiveness of the projects was enhanced, further contributing to the reduction of greenhouse gas emissions from buildings.

This study confirmed the need to improve the energy performance of senior centers, which are mainly used by elderly people over 60 years of age. Among the energy performance improvement projects to be activated to achieve the domestic greenhouse gas reduction target, this study intends to present the effects of each energy performance improvement factor of the senior centers. In addition, an economic feasibility analysis was conducted for each energy performance improvement factor to reduce the energy consumption burden of these centers and their users.

2. Objective

As mentioned in the introduction, it is necessary to improve the energy performance of senior centers, which are mainly used by elderly people in their 60s or older. Prior to an analysis, this study selected the target area by checking the regional status of old senior centers. Presently, the "2nd Green Building Basic Plan" categorizes buildings that have aged more than 20 years since the building completion as old buildings [5]. As shown in Figure 1, the statuses of facilities for the elderly and children, built more than 20 years ago, were analyzed for each region in Korea. [6].



(**a**) (**b**)

(**c**) (**d**)

Figure 1. Number of years since completion of the buildings for the elderly and children in Korea: (**a**) number of buildings aged 20–25 years since completion; (**b**) number of buildings aged 25–30 years since completion; (**c**) number of buildings aged 30–35 years since completion; and (**d**) number of buildings aged > 35 years since completion.

An analysis of the current status of the facilities for the elderly as of 2021 revealed that old buildings aged 20 to 35 years after completion were most concentrated in the Gyeonggi-do province. In addition, it was confirmed that there are many old buildings in Seoul that are over 35 years old.

In Korea, Seoul, Gyeonggi-do, and Incheon are categorized as metropolitan areas. Therefore, this study investigated the effects of enhancing the energy performance of senior centers, specifically targeting the metropolitan areas where buildings for the elderly and children, aged over 20 years, are concentrated. In addition, we conducted an economic feasibility analysis of the improvement factors, and the effect of reducing heating energy charges on the improvement factors was presented. Hence, the objective of this study is to delineate the hierarchical prioritization of the improvement factors aimed at enhancing the energy efficiency of senior centers. This will be accomplished through a comprehensive analysis of the energy performance impact and economic viability associated with each factor.

3. Research Process

To analyze senior center energy performance improvement effects and conduct an economic analysis, we surveyed the energy performance improvement status of the senior centers in the metropolitan area, conducted an ECO2 simulation to diagnose their energy performance, selected standard models, performed an economic analysis, and conducted blower door tests before and after window improvement. In addition, an economic feasibility analysis was performed to analyze the energy cost reduction effect of implementing various building energy performance improvement factors. The research process is depicted in Figure 2.

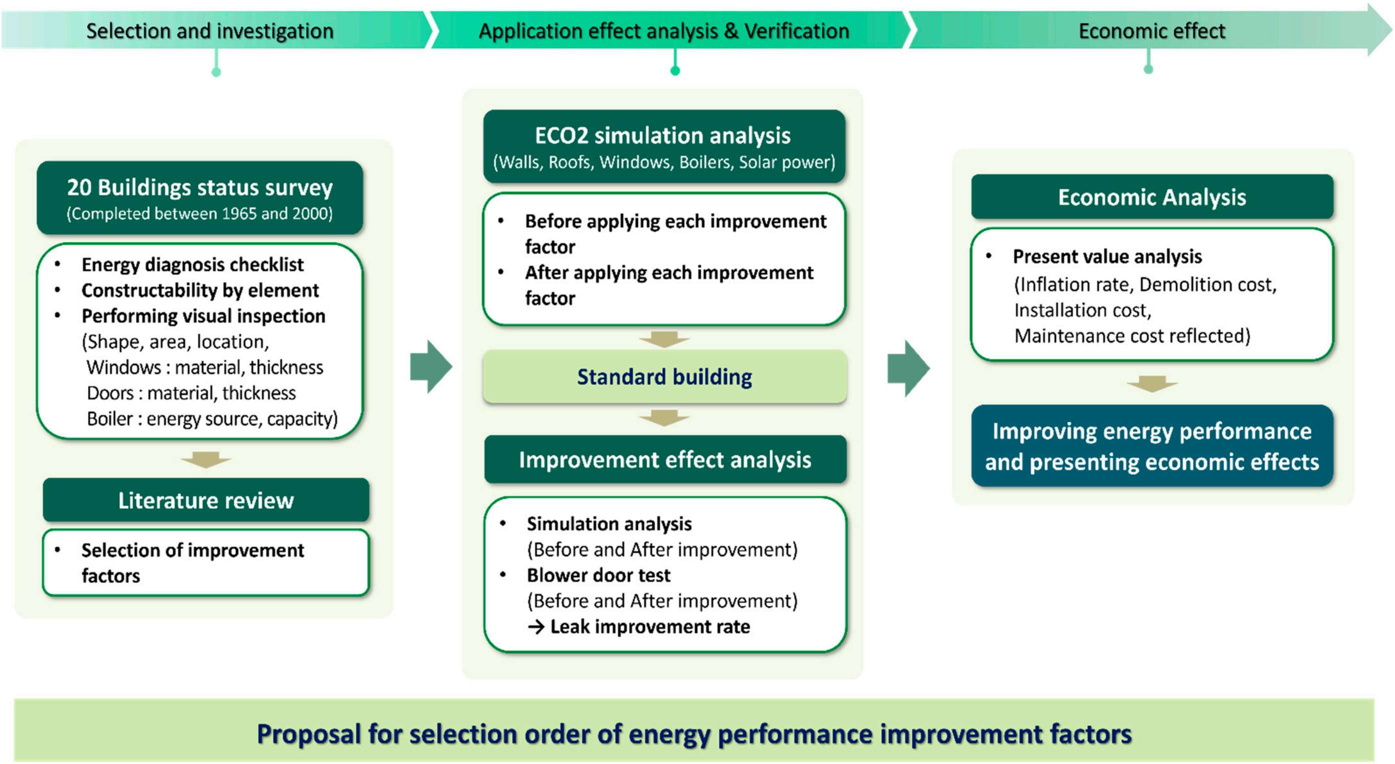


Figure 2. Research process for analyzing the effects and economics of improving the energy performance of senior centers.

Initially, a comprehensive field survey encompassing 20 senior centers, subject to governmental support aimed at enhancing energy performance within the metropolitan region, was undertaken. We collected the existing design documents to analyze energy consumption and other factors, followed by an on-site survey. The on-site survey included user questionnaires, an assessment of the condition and aging status of each building component, an identification of the areas and scopes for improvement, an asbestos inspection, and a visual structural safety assessment. In addition, the energy performance improvement factors were selected via a literature review. Secondly, the energy efficiency of these buildings was evaluated through ECO2 simulations, wherein each selected factor contributing to energy performance enhancement was analyzed. Thirdly, the standard model was chosen by assessing key parameters including energy demand, consumption, primary energy consumption, and the building area derived from the prior ECO2 simulations, with the selection criterion being the median value.

Fourthly, to confirm the improvement in energy performance, constructions aimed at enhancing energy efficiency were carried out in selected older facilities serving the elderly and children in the Seoul metropolitan area. Blower door tests were conducted before and after the improvements to verify the effectiveness of the energy enhancement measures. Based on the results of the ECO2 simulation and blower door test conducted in the third and fourth stages, a method for selecting improvement factors was proposed.

Fifthly, employing a standard model as the framework, this study conducted a detailed analysis of the impact of specific elements on the energy performance improvement of senior centers. This analysis aims to delineate a prioritization process for selecting improvement elements and to evaluate their economic implications.

Finally, this study analyzed the energy performance and economic effect of each improvement element and suggested a method for selecting senior center energy performance improvement elements.

4. Senior Center Energy Performance Diagnosis

To assess the effects of the energy performance improvement measures implemented in the senior centers, an architectural survey of 20 buildings was conducted. Additionally, to evaluate the effectiveness of each energy performance improvement measure, the annual primary energy consumption per unit area was determined by conducting ECO2 simulations.

4.1. Senior Center Status

To examine the conditions of the existing senior centers, the architectural and equipment statuses of 20 buildings were surveyed via their drawings. For the building factors that could not be assessed solely through a visual inspection, such as walls and roofs, the applicable materials were estimated by referring to the relevant insulation application standards based on the year of completion.

4.1.1. Architectural Status

The architectural status of 20 senior centers in the metropolitan area was surveyed based on the year of building completion, building standards at the time of completion, and the visual inspection results. First, in terms of building age, as shown in Table 1, the A-senior center, completed in 1963, is the oldest, while the T-senior center, completed in 1998, is the newest. Most of the buildings were completed between 1980 and 1989.

Table 1. Result of survey on completion year of 20 senior centers in Seoul metropolitan area.

Construction Completion Year	Senior Center
Before 1970	A, B
1970–1979	C, D, E, F, G
1980–1989	H, I, J, K, L, M, N, O
1990–2000	Q, R, S, T

In addition, the external walls and roofs were estimated by analyzing design books, performing a visual inspection, and evaluating the building standards for the year of completion. Through a visual inspection, the shape, area, and space of the buildings were identified, and the materials used for the windows and doors, as well as the energy sources and capacities of the boilers, were analyzed. For the buildings for which it was not possible to obtain the architectural drawings because a long time had elapsed since their completion date, the insulation measures applied to the outer walls and roof were estimated by referring to the building information display and the year of completion [7,8].

The insulation composition and heat transfer coefficient of the outer walls were investigated. As shown in Table 2, the measures to prevent heat loss were initially implemented in 1979 under Article 25 of the Enforcement Rules of the Building Act [8,9]. In addition, in 1992, the measures to prevent heat loss were implemented under the "Rules on Equipment Standards for Buildings" and in 2008, under the "Criteria for Energy Saving Design of Buildings" [10,11]

Table 2. External wall insulation standards in Seoul metropolitan area by revision year.

Revision Year	External Wall Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Building Code Standard
1979	2.093 or 50 mm-thick insulation	Article 25 of Building Act Enforcement Rules
1980	0.581	Article 25 of Building Act Enforcement Rules
1984	0.581 or 50 mm-thick insulation	Article 19 of Building Act Enforcement Rules
1987	0.581 or 50 mm-thick insulation	Article 19 of Building Act Enforcement Rules—Central region
1992	0.581 or 50 mm-thick insulation	Article 21 of Regulations on Equipment Standards for Buildings—Central region

Regarding total floor area, as outlined in Table 3, the highest number of senior centers was observed within the range of 50 m^2 to 150 m^2.

Table 3. Total floor area survey results of 20 senior centers in Seoul metropolitan area.

Total Floor Area (m^2)	Senior Center
Less than 50	P
50–100 or lower	H, I, K, L, M, N, R
100–150 or lower	B, D, E, F, G, J, O, S
More than 150	A, C, Q, T

Therefore, the heat transfer coefficients of the outer walls were estimated by checking the age since the completion year of the senior centers and the implementation date of the standard for the outer wall insulations. According to the results, the estimated heat transfer coefficients of the outer walls before the improvements were 2.093 W/m^{2}K and 0.581 W/m^{2}K, as listed in Table 4. The external finishing materials were verified through a site survey, and the insulation for the exterior walls was assumed to be PF boards, with the insulation thickness calculated in reverse to meet the required overall heat transfer coefficient.

Table 4. Estimated heat transfer coefficients of the exterior walls of 20 senior centers in Seoul metropolitan area.

External Wall Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Senior Center
0.581	H, I, J, K, L, M, N, O, P, Q, R, S, T
2.093	A, B, C, D, E, F, G

The roof heat transfer coefficients were estimated by checking the roof insulation standards enforced in the Seoul metropolitan area by revision year and building age since the year of completion, as shown in Table 5.

Table 5. Roof insulation standards in Seoul metropolitan area by revision year.

Revision Year	Roof Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Building Code Standard
1979	1.047 or 50 mm-thick insulation	Article 25 of Building Act Enforcement Rules
1980	0.581	Article 25 of Building Act Enforcement Rules
1984	0.581 or 50 mm-thick insulation	Article 19 of Building Act Enforcement Rules
1987	0.407 or 50 mm-thick insulation	Article 19 of Building Act Enforcement Rules—Central region
1992	0.407 or 80 mm-thick insulation	Article 21 of Regulations on Equipment Standards for Buildings—Central region

The roof's heat transfer coefficient was estimated based on the completion time of the senior center and the building standards code at that time.

According to the estimates, the roof heat transfer coefficients before the improvements were 0.407 W/m^{2}K, 0.581 W/m^{2}K, and 1.047 W/m^{2}K, as shown in Table 6.

Table 6. Estimated roof heat transfer coefficient values of 20 senior centers in Seoul metropolitan area.

Roof Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Senior Center
0.407	N, O, P, Q, R, S, T
0.581	H, I, J, K, L, M
1.047	A, B, C, D, E, F, G

Regarding windows, this study identified the distinguishable materials, assessed the number of glass layers, and measured the glass thickness. In addition, to understand the heat transfer coefficients and compositions of the windows built in each year, we referred to the Korea Land and Housing Corporation's report "Research on Sound Insulation Design of External Windows", the literature, and the energy-saving design standards [8,10–13].

Table 7 summarizes the compositions and heat transfer coefficients of the windows estimated based on the visual inspection results and the information contained in the reference materials.

Table 7. Results of a survey of major window compositions and heat transfer coefficients of 20 senior centers in Seoul metropolitan area.

Window Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Window Composition	Senior Center
1.8	22 mm (5 mm + 12 mm (Air) + 5 mm), PVC	E, F, R
2.1	16 mm (5 mm + 6 mm (Low-E) + 5 mm), PVC	C, H
2.4	16 mm (5 mm + 6 mm (Air) + 5 mm), PVC	A, B, G, I, J, M, O, P
	10 mm (5 mm + 5 mm), PVC	D, K, L
4	16 mm (5 mm + 6 mm (Air) + 5 mm), AL	N, Q, S
6.6	5 mm, AL	T

A visual inspection confirmed that among the 20 senior centers, with the exception of the D, J, K, L, N, Q, S, and T senior centers, the other buildings had undergone window improvement work at least once in their lifetimes. It was confirmed that the improved polyvinyl chloride (PVC)-framed windows were superior to the aluminum or wooden windows that were typically installed at the time of building completion.

The heat transfer coefficients and compositions of the doors in these buildings were checked via a visual inspection and by referring to the "Energy saving plan design criteria", as listed in Table 8.

Hence, the architectural factors related to the energy improvement of the senior center were identified through field surveys, the literature review, and the legal history.

Table 8. Results of an investigation of major door compositions and heat transfer coefficients of 20 senior centers in Seoul metropolitan area.

Door Insulation Standard (Heat Transfer Coefficient *U*: W/m^{2}K)	Door Composition	Senior Center
2.4	Wood	J
2.7	Steel	H, K, L, M, N, O, P, Q, R, S
5.5	Single glaze	A, B, C, D, E, F, G, I, T

4.1.2. Building Equipment Status

The equipment installed in the senior centers was investigated. The boilers which affect heating energy consumption, were analyzed, and it was found that new and renewable equipment was not installed in all 20 senior centers.

Table 9 lists the main boiler specifications determined via the visual inspections and the attached boiler construction signs. In addition, the visual inspections confirmed that electric boilers were installed as auxiliary equipment in addition to the main boilers.

Table 9. Major boilers installed in 20 senior centers in Seoul metropolitan area.

Boiler Type	Efficiency (%)	Senior Center
Gas	80–83	A, B, C, D, E, F, H, I, J, K, M, N, O, Q, R, S, T
Condensing	86–87	G, L, P

A thorough examination was conducted on the equipment installed within the senior centers. This investigation specifically focused on boilers, which are known to significantly impact heating energy consumption. The findings revealed that none of the 20 senior centers had incorporated new and renewable energy systems. Table 9 lists the boiler specifications determined via the visual inspections and the attached boiler construction signs. In addition, the visual inspections confirmed that electric boilers were installed as auxiliary equipment in addition to the main boilers.

4.2. Energy Performance Diagnosis—Method

To confirm the changes in building energy performance after the improvements to the architectural and facility factors of the 20 senior centers, the differences in the primary energy consumption per unit area of these buildings were analyzed before and after the implementation of the improvements to each building. To assess the variations in primary energy consumption, ECO2s, a building energy simulation program extensively utilized in Korea, were conducted.

ECO2 is a window-based program that calculates building energy requirements and consumption using monthly average weather data. When inputs such as building orientation, architectural features, mechanical systems, renewable energy, building usage, operating hours, and management methods are provided, the program can estimate the building's monthly energy requirements and predict its energy consumption. Energy consumption is categorized into heating, cooling, hot water, lighting, and ventilation. These calculations can then be used to project the building's primary energy consumption and carbon dioxide emissions [14].

4.2.1. Simulation Methods

ECO2 is a building energy consumption assessment program based on ISO 13790 [15] and DIN 18599 [14,16–20]. The ECO2 program is mainly used to perform building energy and zero-energy building assessments [21]. It has also been used for comparative analyses of actual energy consumption and other program results in several studies [22–25]. Thus, this study examined the pre- and post-renovation energy demand, energy consumption, and primary energy consumption of the exterior walls, roofs, windows, and boilers in 20 senior centers that were the recipients of domestic support projects.

4.2.2. Selection of Improvement Factors—Methods

The selection of improvement factors, namely exterior wall insulation, roof insulation, windows, doors, and boilers for the senior centers, was based on prior identifications within this study. The selection of improvement factors was conducted via a literature review to confirm the effects before and after energy performance improvement, as shown in Table 10.

Table 10. Comparison of the literature review—selection of improvement factors for energy performance improvement.

Reference	Contents
[26–28] [29] Major topic	Energy improvement effect of PF (phenolic foam) board exterior wall insulation A study on materials for improved energy conservation in buildings—PF (phenolic foam) board Improvement of exterior wall insulation
[30,31] [29] Major topic	Energy improvement effect of PF (phenolic foam) board roof insulation A study on materials for improved energy conservation in buildings—PF (phenolic foam) board Improvement of roof insulation
[24] [32–34] Major topic	Thermal transmittance rate by window type A study on windows for improved energy conservation in buildings—low-e, double-glazed glass Improvement of window
[24] Major topic	Thermal transmittance rate by door type Improvement of door
[35–37] Major topic	A study on boilers for improved energy conservation in buildings—condensing boiler Improvement of boiler
This work	Selection of improvement factors for energy performance improvement

To improve energy performance, options such as reducing the window area, installing shading devices, adding windproof structures, installing nighttime insulation devices for the windows, implementing inverter control for the rotating equipment, applying LED lighting, and using standby power cut-off outlets could be considered. However, in this study, these measures were not considered due to the difficulty of applying them to small, aging buildings.

4.3. Energy Consumption by Improvement Factor

The improvement factors selected through the literature review were applied to the ECO2 simulations to compare the energy demand, energy consumption, and primary energy consumption before and after the improvement of the exterior walls, roofs, windows, and boilers.

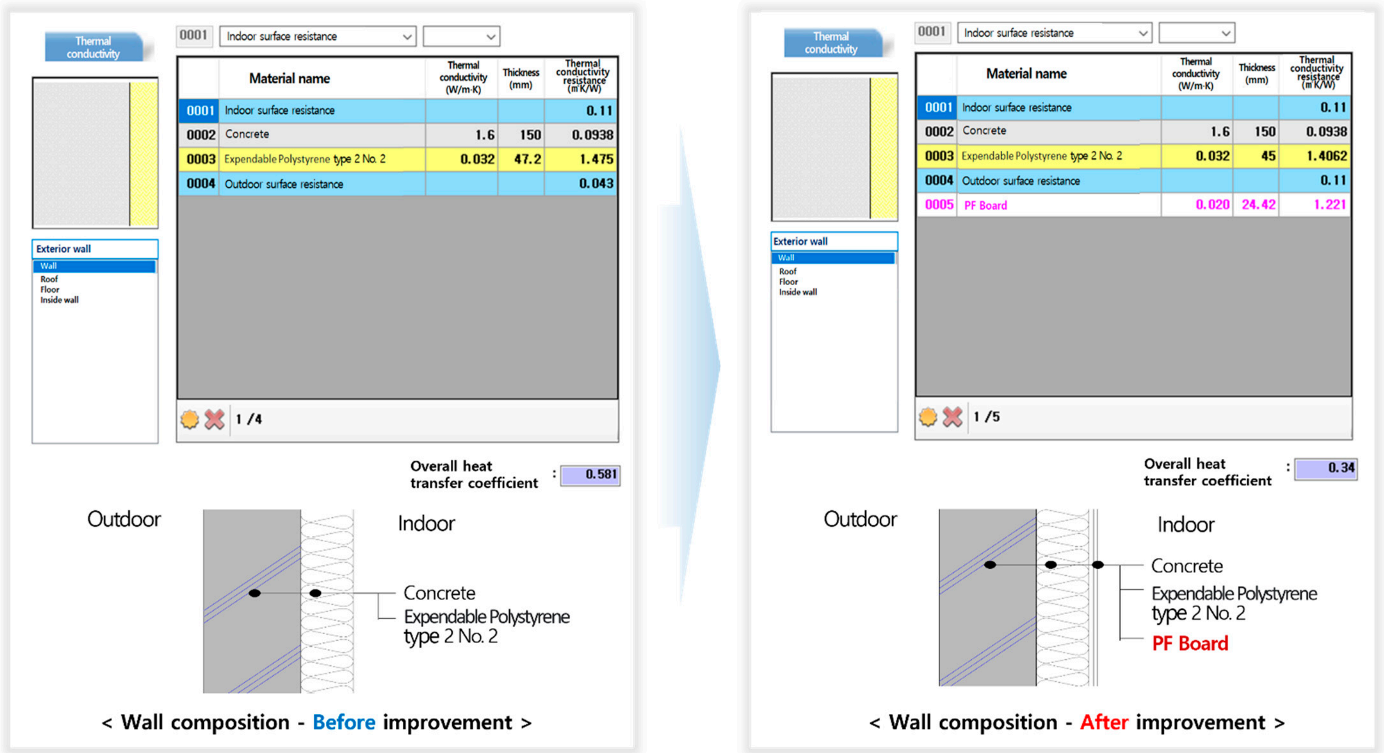
4.3.1. Wall Insulation

The changes in building energy performance after the application of the exterior wall improvements to the 20 senior centers were analyzed. The exterior wall configurations utilized in the ECO2 simulation input were based on the exterior wall conditions outlined in Table 2. The conditions for post-improvement of the exterior walls involved the application of widely used PF boards, ensuring fire resistance performance as required by the relevant regulations [38–40]. Table 11 lists the analysis results of the energy demand, energy consumption, and primary energy consumption before and after the application of PF boards for the improving the external walls. The average decrease in primary energy consumption after the application of the external wall improvements was found to be 25.9%. The senior center with the least improvement effect was analyzed as O. The median value of the primary energy consumption reduction was 14.6% and was with the K-senior center.

Table 11. ECO2 simulation results for energy demand, energy consumption, and primary energy consumption before and after the application of external wall improvements.

Improvement Effect (Analysis of 20 Models)		**Demand or Consumption per Unit Area per Year (Unit: kWh/m^{2}y)**						
		Energy Demand		**Energy Consumption**		**Primary Energy Consumption**		
		Before	**After**	**Before**	**After**	**Before**	**After**	**Improvement Rate (%)**
Lowest	O	114.4	104.7	143.5	129.0	201.9	186.4	8.7
Median	K	127.3	110.4	174.3	148.5	222.5	194.5	14.6
Highest	D	207.8	126.4	296.9	176.7	357.6	225.9	59.3
Average		150.8	116.7	205.3	155.8	260.5	205.6	25.9

Figure 3 shows the ECO2 simulation input screen for the K-senior center, the improvement rate of which was found to be the median value. The heat transfer coefficients of the exterior walls of the K-senior center before and after the application of the exterior wall improvements were 0.581 W/m^{2}K and 0.340 W/m^{2}K, respectively. Therefore, based on the simulation results, the predicted primary energy consumption per unit area per year would decrease by 28 kWh/m^{2}y after the application of PF boards for the exterior wall improvements (Table 11).



	Material name	Thermal conductivity (W/m·K)	Thickness (mm)	Thermal conductivity resistance (m'K/W)
0001	Indoor surface resistance			0.11
0002	Concrete	1.6	150	0.0938
0003	Expendable Polystyrene type 2 No. 2	0.032	47.2	1.475
0004	Outdoor surface resistance			0.043

Overall heat transfer coefficient : 0.581

	Material name	Thermal conductivity (W/m·K)	Thickness (mm)	Thermal conductivity resistance (m'K/W)
0001	Indoor surface resistance			0.11
0002	Concrete	1.6	150	0.0938
0003	Expendable Polystyrene type 2 No. 2	0.032	45	1.4062
0004	Outdoor surface resistance			0.11
0005	PF Board	0.020	24.42	1.221

Overall heat transfer coefficient : 0.34

Figure 3. ECO2 simulation input screen before and after wall improvement at K-senior center.

4.3.2. Roof Insulation

Table 12 shows the results of analyzing the changes in energy performance due to roof improvements for the 20 senior centers using ECO2 simulations, with reference to the values in Table 6. Regarding the material for roof improvement, a PF board, known for its practical effect of enhancement, was applied [38,39]. The average improvement rate of the roofs after the application of a PF board was 6.4%, and the N-senior center exhibited the lowest improvement effect. In addition, the I-senior center exhibited the median improvement effect with an improvement rate of 4.8%. For I senior center, the heat transfer coefficient values before and after the application of the roof improvements were 0.581 W/m^{2}K and 0.150 W/m^{2}K, respectively.

Table 12. ECO2 simulation results of energy demand, energy consumption, and primary energy consumption before and after the application of roof improvements.

Improvement Effect (Analysis of 20 Models)		Demand or Consumption per Unit Area per Year (Unit: kWh/m^{2}y)						
		Energy Demand		Energy Consumption		Primary Energy Consumption		
		Before	After	Before	After	Before	After	Improvement Rate (%)
Lowest	N	142.4	139.1	201.3	196.7	247.8	237.7	4.2
Median	I	125.4	118.8	176.2	166.7	230.9	220.4	4.8
Highest	G	234.5	207.8	290.9	255	371.2	330.8	12.2
Average		150.8	140.4	205.3	190.9	260.5	243.4	6.4

Hence, according to the simulation outcomes, our projections indicate a reduction of 10.5 kWh/m^{2}y in the annual primary energy consumption per unit area subsequent to the implementation of PF boards for roof enhancement (Table 12).

4.3.3. Window

For windows, an ECO2 simulation analysis was conducted for senior centers D, J, K, L, N, Q, S, and T, excluding the 12 centers where window improvement projects had already been carried out. For the post-window improvement condition, low-e double-glazed glass and PVC frames, currently the most widely utilized in energy-saving design standards, were implemented [11,41–43]. According to the results of the ECO2 simulations, the average window improvement rate was 8.0%, and the J-senior center exhibited the least improvement. The K-senior center exhibited the median improvement effect with an improvement rate of 4.4% (Table 13).

Table 13. ECO2 simulation results of energy demand, energy consumption, and primary energy consumption before and after the application of window improvements.

Improvement Effect (D, J, K, L, N, Q, S, T)		Demand or Consumption per Unit Area per Year (Unit: kWh/m^{2}y)						
		Energy Demand		Energy Consumption		Primary Energy Consumption		
		Before	After	Before	After	Before	After	Improvement Rate (%)
Lowest	J	120.3	119.6	171.1	170.9	224.8	224.3	0.1
Median	K	127.3	121.1	174.3	167.0	222.5	213.7	4.4
Highest	S	137.0	110.5	170.9	139.7	222.5	185.6	22.3
Average		141.5	130.6	195.0	181.6	247.2	231.4	8.0

The windows of the K-senior center were composed of 10 mm-thick (5 mm + 5 mm) PVC, and the heat transfer coefficient was 3.1 W/m^2 K. After the improvement with low-e, double-glazed glass, the heat transfer coefficient became 2.1 W/m^2 K. Therefore, based on the simulation results, we anticipated that the primary energy consumption per unit area per year would diminish by 8.8 kWh/m^{2}y with the window enhancement measures.

4.3.4. Door

ECO2 simulations were performed on the door systems of 17 senior centers, with reference to the values in Table 8. The senior centers designated as C, F, and N, where structural alterations to the doors were unfeasible, were excluded from the analysis. As for the conditions after the door improvements, the heat transfer coefficients were applied by referring to the energy-saving design standard. For the door materials, the same materials as before the improvements were applied, considering the structural characteristics. [11].

The ECO2 simulation results indicated that the average door improvement rate was 1.8%, and the R-senior center exhibited the lowest improvement. Among the 17 senior centers considered in this analysis, the S-senior center exhibited the median value, and the corresponding improvement rate was 1.2% (Table 14).

Table 14. ECO2 simulation results of energy demand, energy consumption, and primary energy consumption before and after door improvements.

Improvement Effect (A, B, D, E, G, H, I, J, K, L, M, N, O, P, Q, R, S, T)		Demand or Consumption per Unit Area per Year (Unit: kWh/m^{2}y)						
		Energy Demand		Energy Consumption		Primary Energy Consumption		
		Before	After	Before	After	Before	After	Improvement Rate (%)
Lowest	D	207.8	206.5	296.9	295.4	357.6	355.6	0.6
Median	S	137.0	135.4	170.9	168.3	222.5	219.8	1.2
Highest	R	115.0	110.5	160.7	154.1	210.7	203.5	3.5
Average		146.3	143.8	199.8	196.7	255.2	250.5	1.8

The doors used in the S-senior center were made of steel, and the overall heat transfer coefficient was 2.7 W/m^2 K. After the door improvements, the applied overall heat transfer coefficient of the doors was 1.7 W/m^2 K. The simulation predicts that the annual primary energy consumption per unit area will decrease by 2.7 kWh/㎡y when applying door renovations.

4.3.5. Boiler

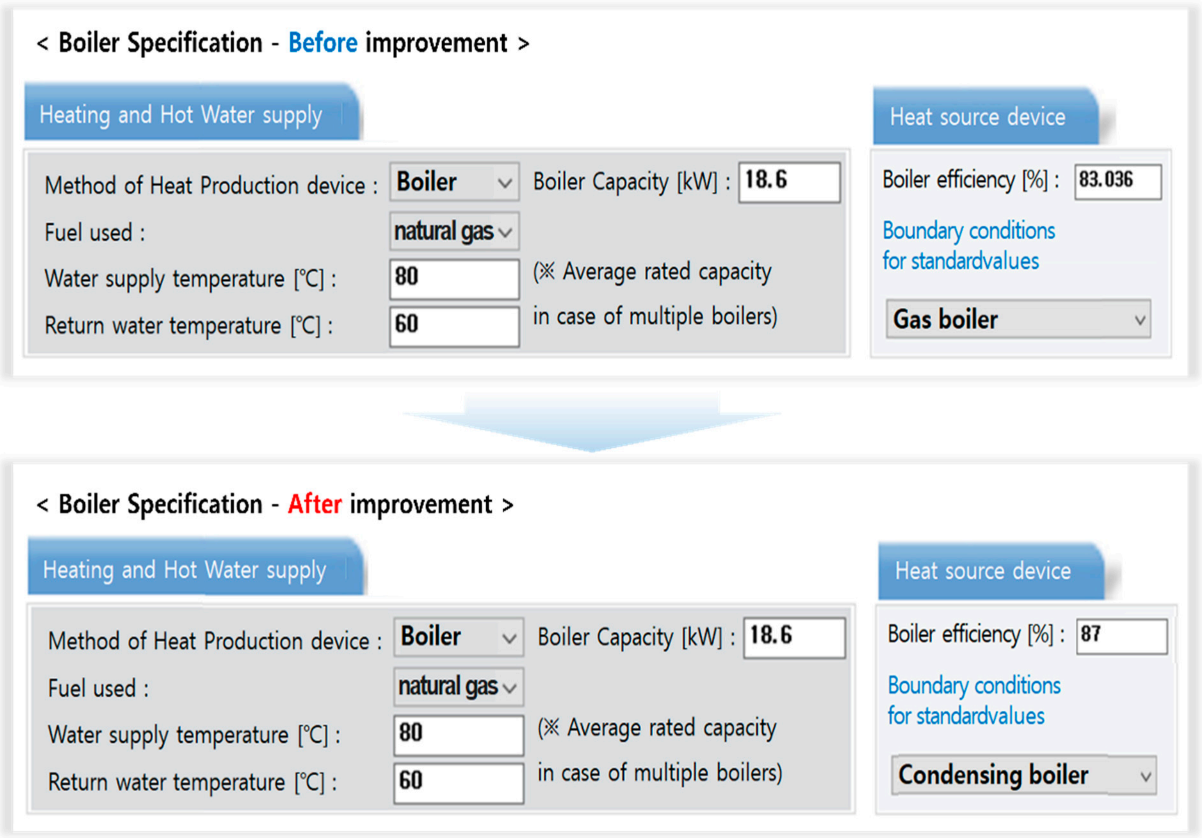
An ECO2 simulation analysis was conducted on 17 senior centers, excluding G, L, and P, where condensing boilers was already applied, as referenced in Table 9. The conditions for boiler improvement involved the application of condensing boilers characterized by low nitrogen oxide emissions and a high thermal efficiency [44,45].

The ECO2 simulation results indicated that the average improvement rate was 6.5%, as listed in Table 15, and the C-senior center exhibited the lowest improvement effect. The N-senior center showed the median improvement effect among the 17 senior centers, with a corresponding improvement rate of 8.2% (Table 15).

Table 15. ECO2 simulation analysis results of boilers before and after improvements: energy demand, energy consumption, and primary energy consumption.

Improvement Effect (A, B, C, D, E, F, H, I, J, K, M, N, O, Q, R, S, T)		Demand or Consumption per Unit Area per Year (Unit: kWh/m^{2}y)						
		Energy Demand		Energy Consumption		Primary Energy Consumption		
		Before	After	Before	After	Before	After	Improvement Rate (%)
Lowest	C	209.1	209.1	269.4	262.5	337.8	331.3	2.0
Median	N	142.4	142.4	201.3	187.8	247.8	229.0	8.2
Highest	I	125.4	125.4	176.2	158.3	230.9	212.0	8.9
Average		149.0	149.0	202.8	188.9	257.0	241.6	6.5

Figure 4 shows the ECO2 simulation input screens of the N-senior center, which exhibited the median improvement effect. In the N-senior center, 18.6 kW gas boilers were installed on both the first and second floors before the improvement. After the improvement, they were replaced with condensing boilers of the same capacities. Therefore, the simulation predicts that the annual primary energy consumption per unit area will decrease by 18.8 kWh/㎡·y with the boiler renovation.



< Boiler Specification - Before improvement >

Heating and Hot Water supply

Method of Heat Production device : Boiler

Boiler Capacity [kW] : 18.6

Fuel used : natural gas

Water supply temperature [°C] : 80

Return water temperature [°C] : 60

(※ Average rated capacity in case of multiple boilers)

Heat source device

Boiler efficiency [%] : 83.036

Boundary conditions for standardvalues

Gas boiler

< Boiler Specification - After improvement >

Heating and Hot Water supply

Method of Heat Production device : Boiler

Boiler Capacity [kW] : 18.6

Fuel used : natural gas

Water supply temperature [°C] : 80

Return water temperature [°C] : 60

(※ Average rated capacity in case of multiple boilers)

Heat source device

Boiler efficiency [%] : 87

Boundary conditions for standardvalues

Condensing boiler

Figure 4. ECO2 simulation input screens of N-senior center before and after boiler improvement.

5. Standard Models

Subsequently, a standard model for the senior centers was selected to validate the earlier ECO2 simulation results and analyze the economic impact of the primary energy improvement measures.

5.1. Selection of Standard Models

Among the 20 senior centers, the standard models were determined based on the ECO2 simulation results. Following an analysis of the average characteristics related to floor area, energy demand, energy consumption, and primary energy consumption, which had the most significant impact on annual primary energy consumption, the standard models were selected, as outlined in Table 16. Table 16 specifies the average characteristics, designated as J, K, and S, for each condition, representing the standard models for the senior centers.

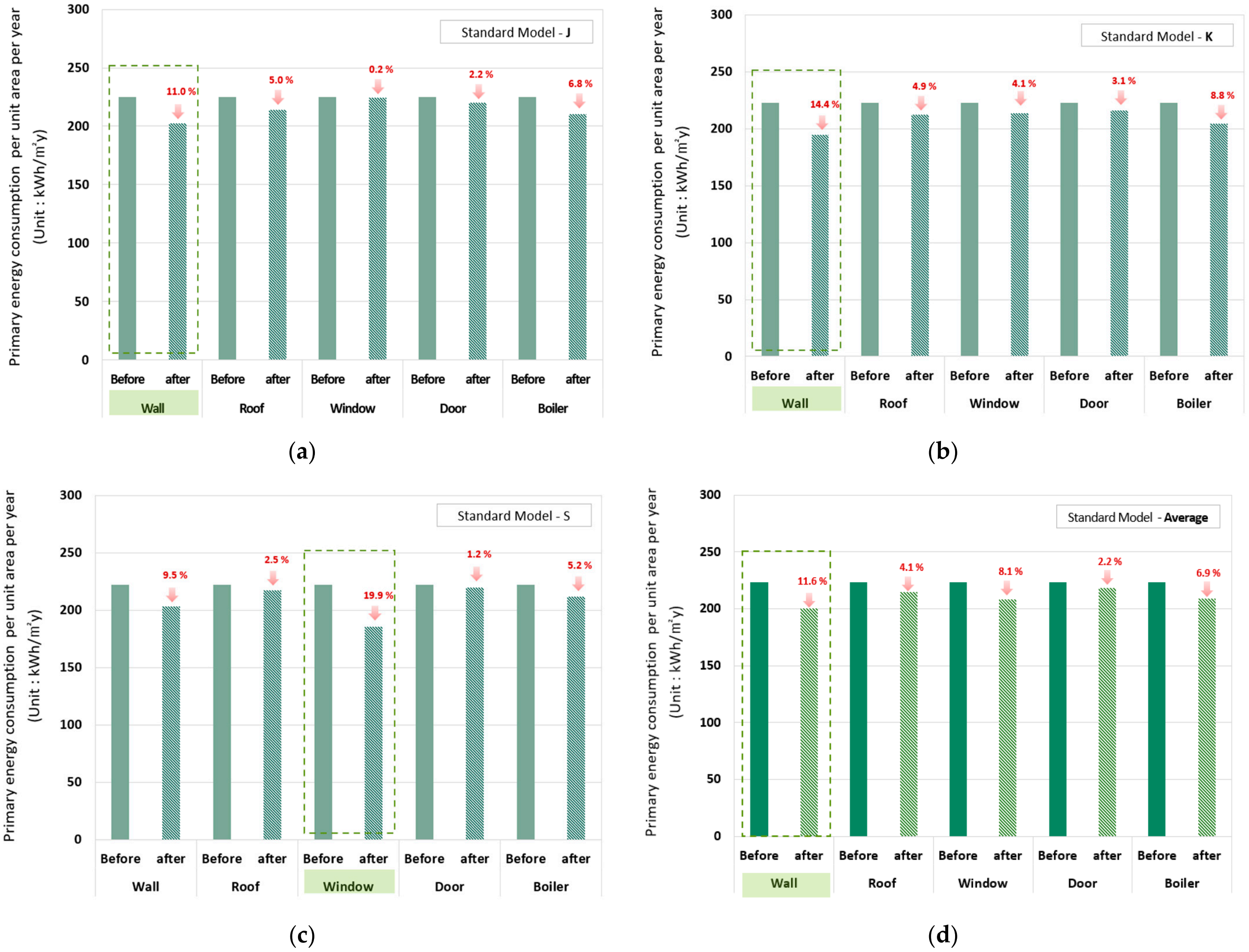
Table 16. Selected standard models based on median values of each category of 20 senior centers in the metropolitan area.

Division	Standard Model
Total floor area	S
Annual energy requirement per unit area	
Annual energy consumption per unit area	K
Annual primary energy consumption per unit area	J

Table 17 shows the results of the ECO2 analysis of the primary energy consumption before and after the energy performance improvements were applied to the standard models J, K, and S. According to the results of a standard model energy performance improvement analysis, as shown in Figure 5, the improvements to the exterior walls had the strongest effects on models J and K, and the window improvements had the strongest effect on model S as shown by dotted boxes. Overall, the element that showed the greatest improvement was determined to be the windows.

Table 17. ECO2 simulation results showing primary energy consumption after application of improvements to outer walls, roofs, windows, doors, and boilers in standard models J, K, and S.

Standard Model	Annual Primary Energy Consumption per Unit Area (Unit: kWh/m^{2}y)									
	Wall		Roof		Window		Door		Boiler	
	Before	After	Before	After	Before	After	Before	After	Before	After
J	224.8	202.5	224.80	214.20	224.80	224.30	224.80	220.00	224.80	210.50
K	222.5	194.5	222.50	212.10	222.50	213.70	222.50	215.80	222.50	204.50
S	222.5	203.2	222.50	217.10	222.50	185.60	222.50	219.80	222.50	211.60
Average	223.3	200.1	223.3	214.5	223.3	207.9	223.3	218.5	223.3	208.9



(**a**) (**b**)

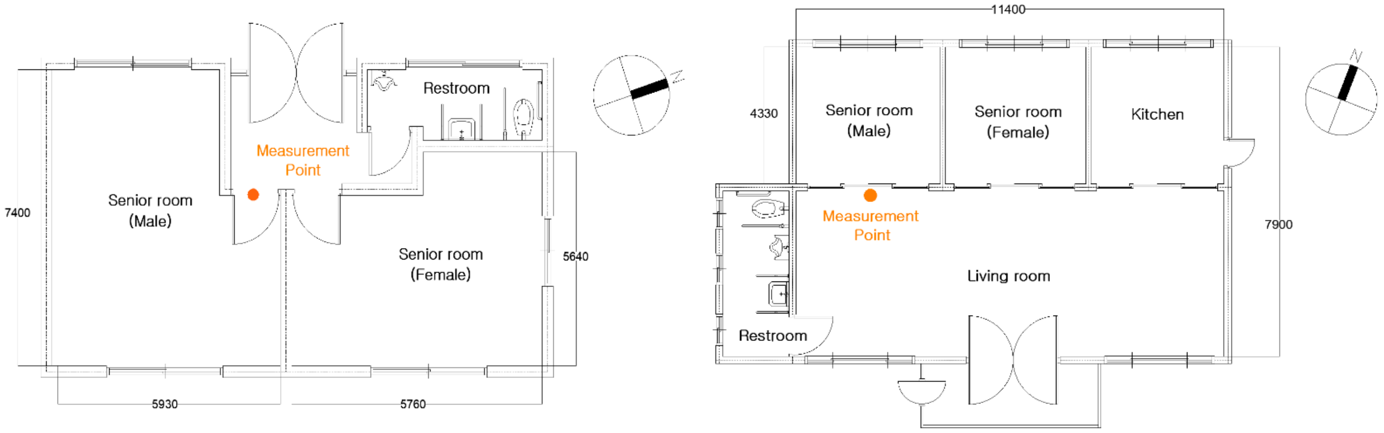
(**c**) (**d**)

Figure 5. ECO2 primary energy consumption analysis results by applying exterior wall, roof, window, door, and boiler improvements to standard models J, K, and S: (**a**) ECO2 primary energy consumption analysis results of standard models J, (**b**) K, and (**c**) S. (**d**) ECO2 simulation results of average primary energy consumption of standard models J, K, and S.

Next, the energy performance improvement effect of the window improvements was verified.

5.2. Verification of Energy Performance Improvement

To validate the improvements observed in the windows with the most significant impact, this study selected aged senior centers within the metropolitan area and conducted simulations and verification experiments. Figure 6 presents diagrams of the α- and β-senior centers, where the verification experiment was conducted. To determine the composition of the windows in the α- and β-senior centers, the window thickness was measured using an EDTM Glass-Chek Pro GC3000 instrument. As shown in Table 18, the windows of the α-senior center were 6 mm thick and composed of PVC frames, while the windows of the β-senior center were 6 mm thick and composed of aluminum frames. For the window and door improvements, a heat transfer coefficient of 1.8 W/m^{2}K, an overall thickness of 22 mm (5 mm + 12 mm (Air) + 5 mm), and PVC frames were applied.



(**a**) (**b**)

Figure 6. Drawing of blower door test site: (**a**) α-senior center with an area of 114 m^2 and (**b**) β-senior center with an area of 115 m^2.

Table 18. Construction completion years of α- and β-senior centers, and compositions of the applied windows.

Senior Center	Construction Completion Year	Window Insulation Standard (Thermal Transmittance *U*: W/m^{2}K)	Window Composition
α	1996	5.3	6 mm, PVC
β	2000	6.6	6 mm, AL

5.2.1. Simulation Analysis

To verify the improvement effect, an ECO2 simulation analysis was conducted. According to the ECO2 simulation, in the case of the α-senior center, the heating energy improvement rate of primary energy consumption was 28.5%, as illustrated in Figure 7. In the case of the β-senior center, the heating energy improvement rate of primary energy consumption was 17.1%, as illustrated in Figure 8. Therefore, the total energy demand and consumption improved when the windows were improved. The energy improvement had a greater impact on heating energy consumption than on cooling energy consumption [46,47].

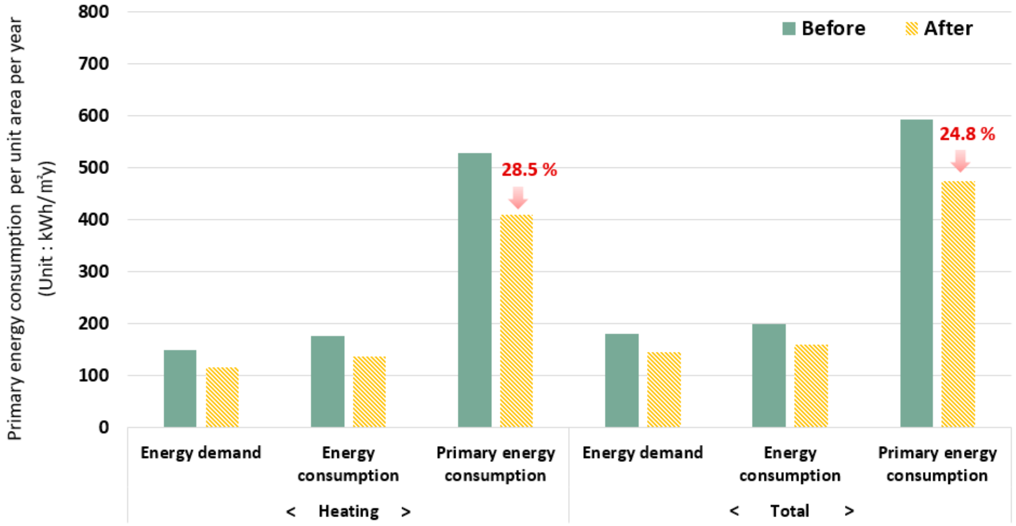


Figure 7. ECO2 simulation results of α-senior center after window improvements.

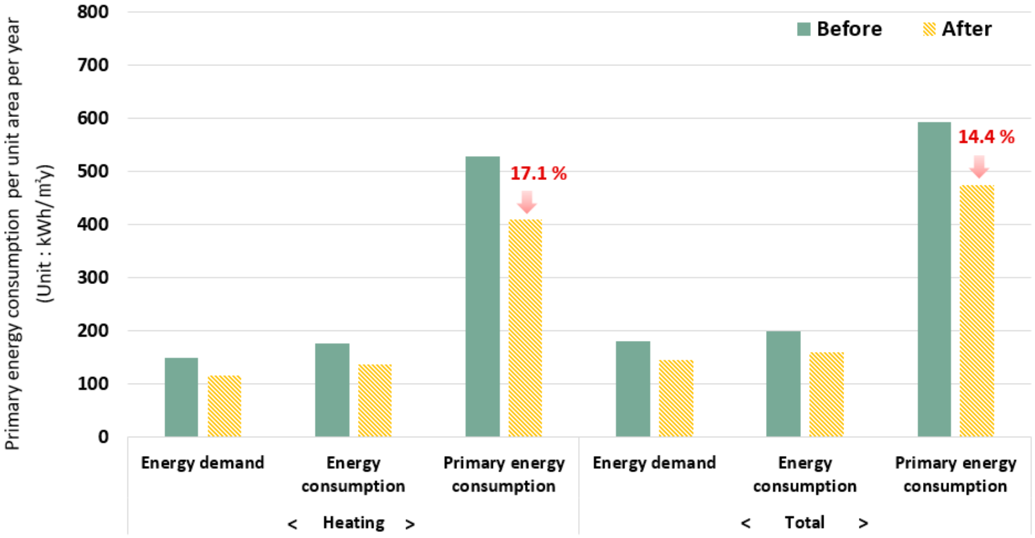
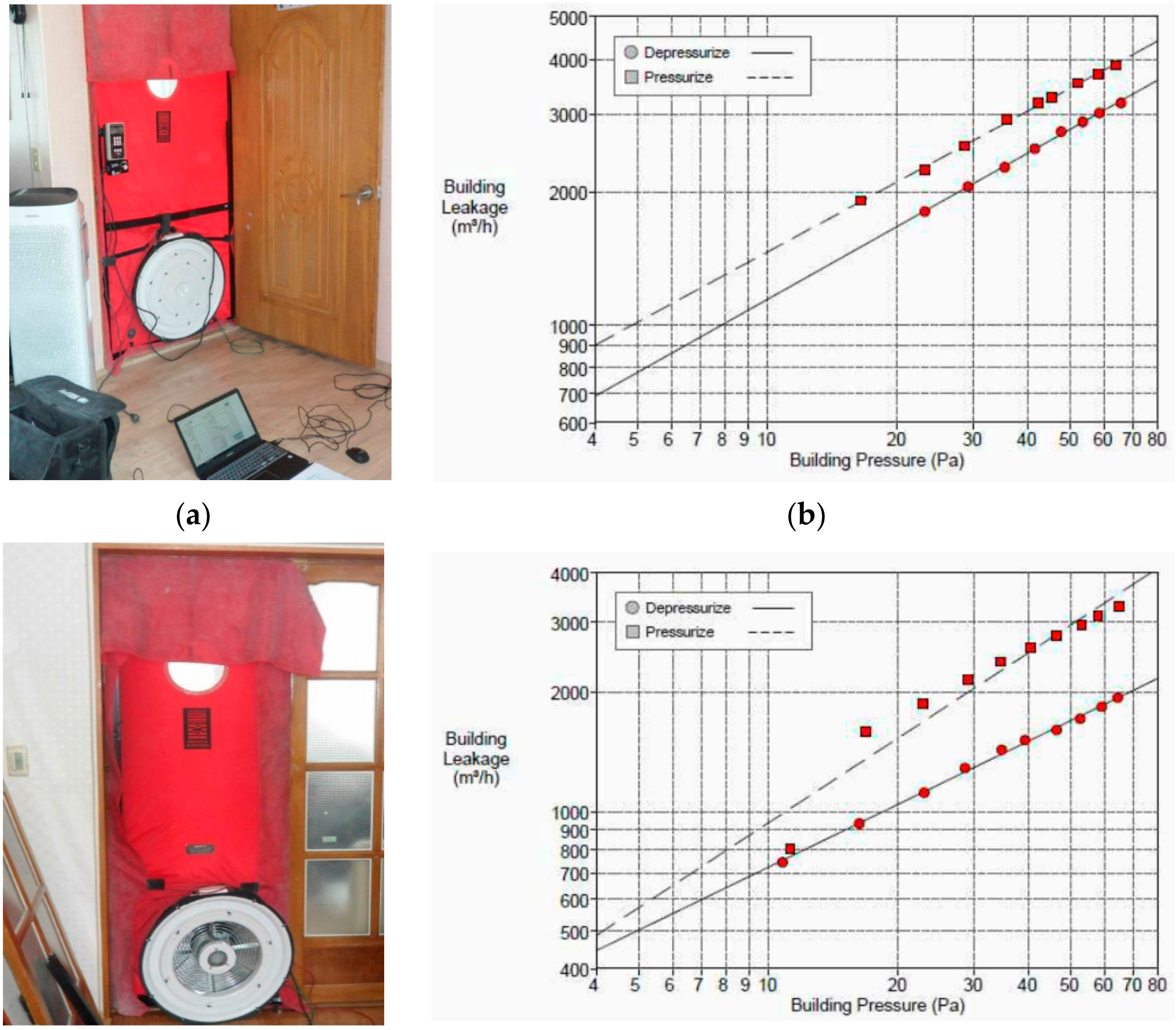


Figure 8. ECO2 simulation results of β -senior center after window improvements.

In this study, the results of the heating energy performance improvements by simulation were verified by measuring the airtightness before and after the window improvements [26,27,48].

5.2.2. Blower Door Test

The improvement in airtightness due to window improvements affects both the heating energy demand and consumption. The strong correlation between airtightness and energy consumption was confirmed by Jeon [48] and Choi [26]. Therefore, airtightness measurement experiments were conducted to verify the energy performance improvements of the windows and doors. The measurement was taken in the male room (39.3 m^2) of the α-senior center and the male room (16.9 m^2) of the β-senior center, as shown in Figure 6. The airtightness test was conducted after installing a blower fan (TEC Minneapolis Blower Door™ System, Minneapolis, MN, USA) at the door, as shown in (a) and (c) of Figure 9. The blower door test was conducted under indoor and outdoor pressure difference conditions ranging from 10 to 65 Pa, following the positive/negative pressurization method (ASTM E779) [28–30]. The airtightness was measured more than eight times using the pressurization and depressurization methods for the pressure range of 10–65 Pa.



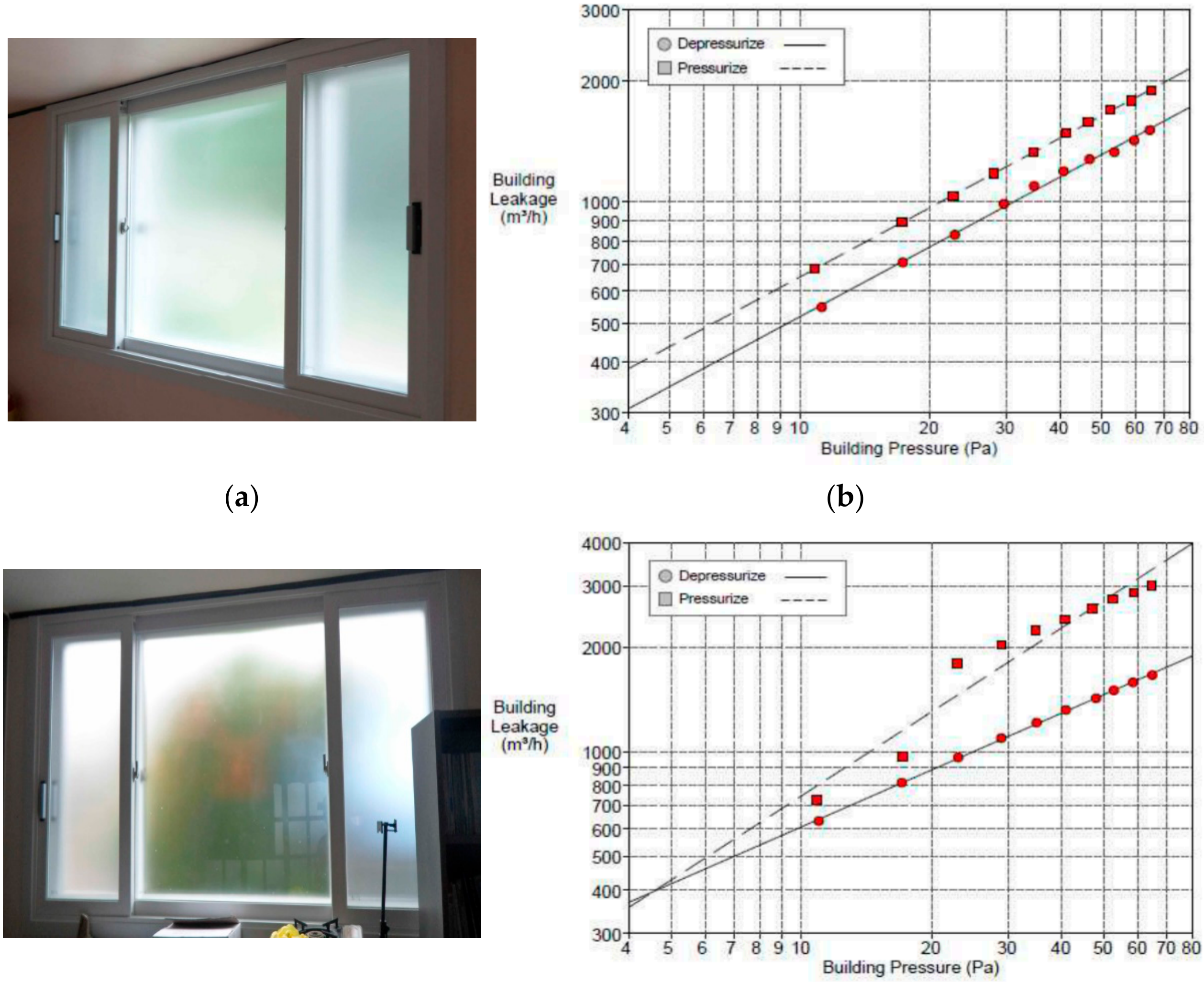
(**a**) (**b**)

(**c**) (**d**)

Figure 9. Experimental setup and results of blower door test before window construction: (**a**) blower door test conducted at α-senior center, and (**b**) test results at α-senior center. (**c**) Blower door test conducted at β-senior center, and (**d**) test results at β-senior center.

According to the results of the blower door test conducted before the window improvements, the building infiltration in the α-senior center was 2271 m^3/h with a pressure difference of 50 Pa during depressurization, and 3435 m^3/h with a pressure difference of 50 Pa during pressurization. In the β-senior center, the building infiltration was 1693 m^3/h with a pressure difference of 50 Pa during depressurization and 2945 m^3/h with a pressure difference of 50 Pa during pressurization.

The results of the blower door test conducted after the window improvements are depicted in Figure 10. In the α-senior center, the building infiltration was 1310 m^3/h with a pressure difference of 50 Pa during depressurization, and 1636 m^3/h with a pressure difference of 50 Pa during pressurization. In the β-senior center, the building infiltration was 1461 m^3/h with a pressure difference of 50 Pa during depressurization, and 2724 m^3/h with a pressure difference of 50 Pa during pressurization.



(**a**) (**b**)

(**c**) (**d**)

Figure 10. Blower door test after window improvement: (**a**) photograph of window constructed in α-senior center, and (**b**) blower door test results under depressurization and pressurization at α-senior center. (**c**) Photograph of window constructed in β-senior center, and (**d**) blower door test results under depressurization and pressurization at β-senior center.

The results of the blower door test for the α- and β-senior centers were analyzed and converted into air change per hour (ACH) as shown in Table 19.

Table 19. Air change per hour (ACH) of α- and β-senior centers according to the blower door test results. Pressure difference = 50 Pa.

Category		Depressurization ACH (1/h)	Pressurization ACH (1/h)	Average ACH (1/h)
α-senior center	Before	25.16	31.18	28.17
	After	11.90	14.86	13.38
	Improvement rate	52.70%	52.34%	52.50%
β-senior center	Before	39.21	68.19	53.70
	After	33.83	63.07	48.45
	Improvement rate	13.72%	7.51%	9.78%

The measured air change per hour (ACH) showed an improvement of 52.34% for the α-senior center, which was approximately 35.24% higher than the simulation result. For the β-senior center, the measured improvement was approximately 4.62% lower than the simulated improvement effect of 9.78%. Therefore, we concluded that the ACH could be improved by at least 9.78% by replacing the existing single-pane windows.

Therefore, when prioritizing energy performance improvement factors in senior centers, an energy consumption analysis through a detailed diagnosis of each performance improvement factor is the most reliable method, but if a detailed diagnosis is difficult, it is suggested to carry out improvements based on the process presented in this study.

The increase in a heating load due to an infiltration is calculated using the following equation.

$$\dot{Q} = \rho c_p V (t_i - t_o) \tag{1}$$

Here, ρ represents the density, c_p denotes the specific heat of air at a constant pressure, n is the air changes per hour, V is the volume of the space, t_i is the indoor temperature, and t_o is the outdoor temperature. The indoor temperature is assumed to be 26 °C.

The reduction in the heating load due to the infiltration improvement is 33.1 kWh/(m^2 y) from the ECO2 simulation and 32.1 kWh/(m^2 y) from the blower door test. As shown in Table 20, the two results show an error of 3.0%, indicating that the ECO2 simulation accurately predicts the actual heating load.

Table 20. Conditions of α center for heating load calculations due to infiltrations.

		Average Outdoor (°C)	**Air Density (kg/m^3)**	**Operation Time per Day (h)**	**Day of Use per Month (d)**	**ACH 50 Pa (1/h)**	**ACH 10 Pa (1/h)**	**Infiltration (cmh)**	**Heat Loss (kWh)**	**Annual Heat Loss per Area (kWh/m^2 y)**
December	Before	0.9	1.287	8	21	28.17	5.634	509.26	770.78	19.61
	After					13.38	2.676	241.88	366.10	9.32
January	Before	−2.1	1.301	8	22	28.17	5.634	509.26	913.83	23.25
	After					13.38	2.676	241.88	434.04	11.04
February	Before	0.2	1.290	8	19	28.17	5.634	509.26	718.49	18.28
	After					13.38	2.676	241.88	341.26	8.68

As described in Figure 11, the first step is to check whether the window has been remodeled through a visual inspection. Next, if the windows have not been remodeled, priority is given to improving the windows, and if the windows have already been remodeled, improvement of the exterior wall insulation, replacement with a high-efficiency condensing boiler, and replacement of the roof insulation are suggested.

This study also included an economic analysis of the standard model to analyze not only the effect of improving energy performance, but also the economic burden caused by the construction.

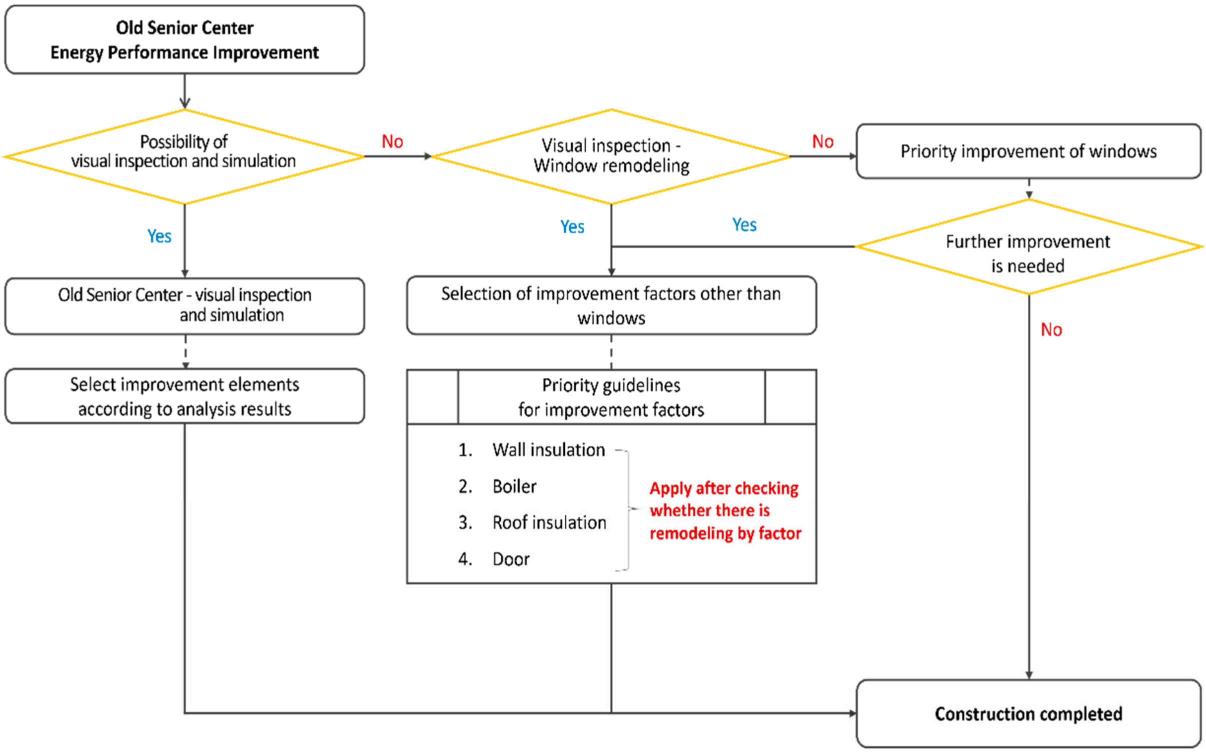


Figure 11. Energy performance improvement factor selection step considering the energy improvement effect.

5.3. Economic Analysis of the Standard Model

To analyze the economic effect of improvements, the annual heating energy cost and life cycle cost of the standard model were conducted [31–34].

In the economic analysis, product price, labor cost, demolition cost, additional costs (asbestos removal costs, structural maintenance costs, electric capacity expansion costs, etc.), and waste disposal cost were considered [34,35].

The unit cost analysis results for the J-senior center are shown in Table 21, for the S-senior center in Table 22, and for the K-senior center in Table 23. The results show that the highest improvement construction cost is for the exterior wall, followed by the window, roof, and boiler, respectively.

Table 21. Unit cost analysis of energy improvement construction in J-senior center.

	Wall (Area: 173.28 m^2)	**Window (Area: 15.17 m^2)**	**Roof (Area: 43.68 m^2)**	**Boiler (18.6, 34.9 kW)**
Product price	20,152 (153,315 KRW/m^2)	3795 (329,791 KRW/m^2)	2323 (70,121 KRW/m^2)	1115
Labor cost	2592 (37,429 KRW/m^2)	628 (54,572 KRW/m^2)	207 (6256 KRW/m^2)	358
Demolition cost	2328	158	587	215
Additional cost	6823	1327	759	-
Waste disposal cost	682	133	76	44
Total cost	32,577	6041	3953	1732

Costs as of 18 April 2023 (unit: USD 1 = KRW 1318.3).

Table 22. Unit price analysis of energy improvement construction in S-senior center.

	Wall (Area: 132.35 m^2)	**Window (Area: 48.67 m^2)**	**Roof (Area: 29.9 m^2)**	**Boiler (18.6, 18.6 kW)**
Product price	15,392 (153,315 KRW/m^2)	12,175 (329,791 KRW/m^2)	1590 (70,121 KRW/m^2)	956
Labor cost	1979 (37,429 KRW/m^2)	2015 (54,572.3 KRW/m^2)	142 (6256 KRW/m^2)	314
Demolition cost	1778	278	402	188
Additional cost	5211	4257	520	-
Waste disposal cost	521	426	52	188
Total cost	24,882	19,151	2706	1646

Costs as of 18 April 2023 (unit: USD 1 = KRW 1318.3).

Table 23. Energy improvement construction unit price analysis results of K-senior center.

	Wall (Area: 132.35 m^2)	**Window (Area: 16.87 m^2)**	**Roof (Area: 51.72 m^2)**	**Boiler (22.8 kW)**
Product price	13,921 (153,315 KRW/m^2)	4220 (329,791 KRW/m^2)	2751 (70,121 KRW/m^2)	546
Labor cost	1790 (37,429 KRW/m^2)	698 (54,572.3 KRW/m^2)	245 (6256 KRW/m^2)	169
Demolition cost	1608	118	695	102
Additional cost	4713	1476	899	-
Waste disposal cost	471	148	90	21
Total cost	22,504	6660	4680	839

Costs as of 18 April 2023 (unit: USD 1 = 1318.3 KRW).

As shown in the table, the construction costs for improving elderly facility elements are substantial. However, when undertaking energy performance improvement projects for elderly care facilities, the government provides partial financial support for the construction costs [36,37]. Currently, in order to reduce greenhouse gas emissions, the government is implementing green remodeling policies and energy improvement projects in facilities for the elderly and children [49–51]. Therefore, participation in various government support projects is expected to reduce the construction costs of such improvements.

The lifecycle analysis of this study excluded the asset value appreciation rate, focusing solely on heating energy consumption, which accounts for the highest usage [31,33,34,52]. The heating energy, maintenance, and replacement costs were analyzed using the present value analysis method, taking into account the inflation rate [1].

To determine the annual heating consumption rate, the primary heating energy consumption obtained from the ECO2 simulation was computed [31,34,53]. Heating energy costs were calculated by analyzing the consumption of primary fuel, LNG, and electricity.

Equations (2) and (3) were used for the annual heating energy consumption per unit area to derive the gas heating rates and power usage rates.

The formula for the gas heating cost is given by Equation (2).

$$C_f = C_{af}\, E_{hec,f}\, A_s \tag{2}$$

The variables in Equation (2) are defined as follows:

C_f: Heating energy cost (USD).
C_{af}: Average gas heating unit cost (USD/Mcal).
$E_{hec,f}$: Annual heating energy consumption per unit area (kWh/m^2).
A_s: Total floor area of the senior center (m^2).

The gas unit price was determined based on the seasonal gas cost in the metropolitan area, 0.0620 USD/Mcal during the winter season and 0.0613 USD/Mcal for the other seasons [54].

The formula for the electric power cost is expressed as Equation (3).

$$C_p = C_{ap}\, E_{hec,p}\, A_s + C_B \tag{3}$$

The variables in Equation (3) are defined as follows:

C_p: Electric power energy cost (USD).
C_{ap}: Average electric power unit cost (USD/kWh).
$E_{hec,p}$: Annual heating energy consumption per unit area (kWh/m^2).
A_s: Total floor area of the senior center (m^2).
C_B: Additional factor over basic cost (USD).

In Equation (3), an electric unit cost of 0.074 USD/kWh was applied by referring to seasonal electricity rate data, and for a base rate of C_B, USD 0.690 was applied. By using Equations (2) and (3), the energy costs according to the annual heating energy consumption per unit area before and after the improvements were calculated [31,34,53].

In this study, a life cycle cost analysis was conducted for a 40-year period. In accordance with the building's age, remodeling or reconstruction of the exterior walls, windows, and roof was undertaken [54–57]. For the life cycle cost analysis, the present value coefficient and the present value coefficient of annuity were computed using Equations (4) and (5).

The present value coefficient formula (3) was applied to the equipment maintenance and replacement costs. The assumption is made that boiler replacements occur every ten years. Therefore, it was assumed that boiler replacements occurred four times during a 40-year lifespan [58].

The discount rate of 1.89%, representing the average annual increase in household gas and electricity tariffs from 2012 to 2022, was applied to calculate the present value coefficient and annuity present value coefficient [1].

The present value coefficient formula is expressed as Equation (4).

$$F_C = \frac{1}{(1+r)^n} \tag{4}$$

The variables in Equation (4) are defined as follows:

F_C: Present value coefficient (-).
r: Average consumer price inflation rate between 2012 and 2022 (-).

The formula for the annuity present value coefficient is given in Equation (5).

$$F_{EC} = \frac{(1+r)^n - 1}{r(1+r)^n} \tag{5}$$

The variables in Equation (5) are defined as follows:

F_{EC}: Annuity present value coefficient (-).
r: Average consumer price inflation rate between 2012 and 2022 (-).

Furthermore, as mentioned in previous research, a supplementary life cycle analysis was conducted to reflect the sharp inflation in 2022, incorporating a 5.5% inflation rate for that year [1].

Based on the results of the life cycle cost analysis of the heating costs over 40 years for the enhancement of the exterior walls, windows, and roofs, as summarized in Table 24, it was confirmed that the implementation of the enhancements provided no economic benefit. However, when receiving construction subsidies, the improvement in heating costs was most significantly observed in the window enhancement of the S model. In addition, when accounting for the construction cost subsidies, the wall factor yielded the greatest average improvement benefit across the J, K, and S standard models.

Table 24. Results of life cycle cost analysis conducted over 40 years for improvement of each factor in the standard models J, K, and S.

Improvement Factor	Senior Center	Annuity Present Value Coefficient	Energy Cost		* Profit (USD)
		** 1.89%	Before (USD/y)	After (USD/y)	** 1.89%
Wall	J	27.89	762	642	−29,230
	K		482	393	−20,022
	S		833	721	−21,758
Window	J		762	762	−6041
	K		482	460	−6046
	S		833	653	−14,214
Roof	J		762	707	−2419
	K		482	450	−3788
	S		833	803	−1869

Costs as of 18 April 2023 (unit: USD 1 = 1318.3 KRW). * Amount may change depending on the building condition. Installation cost (including mechanical, electrical, and labor). ** 1.89%: average consumer price inflation rate between 2012 and 2022.

Table 25 shows the results of the present value analysis of the life cycle costs of boiler maintenance and replacement over a 40-year period. The cost of replacing an aging boiler was analyzed based on the model from Company B.

Table 25. Results of life cycle analysis of boiler replacement over 40 years following boiler improvement of standard models J, K, and S.

Inflation Rate	Year	Present Value Coefficient	Construction Cost by Year When Considering the Present Value Factor					
			J		K		S	
			Before	After	Before	After	Before	After
1.89%	* Construction cost		1019	1732	1019	839	1019	1496
	10	0.829	845	1436	845	696	845	1241
	20	0.688	700	1191	700	577	700	1029
	30	0.570	581	987	581	478	581	853
	40	0.473	482	819	482	397	482	707
	Sum		3626	6164	3626	2986	3626	5326
Construction Profit			−2538		640		−1700	

Costs as of 18 April 2023 (unit: USD 1 = 1318.3 KRW). * Costs of condensing boilers are subsidized by the government.

As shown in Table 24, only the K model was analyzed to be economically viable. In the case of the K model, the building was small, so a boiler with a small capacity was sufficient, making it economically feasible.

Table 26 presents the results of the 40-year life cycle cost analysis of the heating costs based on boiler operations.

Table 26. Life cycle analysis results considering heating costs over 40 years after boiler improvements in standard models J, K, and S.

Improvement Factor	Senior Center	Present Value Coefficient of Annuity	Energy Cost		Energy Profit (USD)	* Total Profit (USD)
		** 1.89%	Before	After	** 1.89%	** 1.89%
Boiler	J	27.89	762	717	1255	−1.238
	K		482	442	1116	1756
	S		833	793	1116	−584

Costs as of 18 April 2023 (unit: USD 1 = 1318.3 KRW). * Amount may change depending on the building condition. Installation cost (including mechanical, electrical, and labor). ** 1.89%: average consumer price inflation rate between 2012 and 2022.

Therefore, when construction costs are not supported, the economic benefit is negative in all the cases. However, replacing a standard boiler with a condensing boiler resulted in the smallest deficit.

As a result of the life cycle cost analysis, as shown in Figure 12, only the boiler for the K model was found to generate benefits in total costs over 40 years.

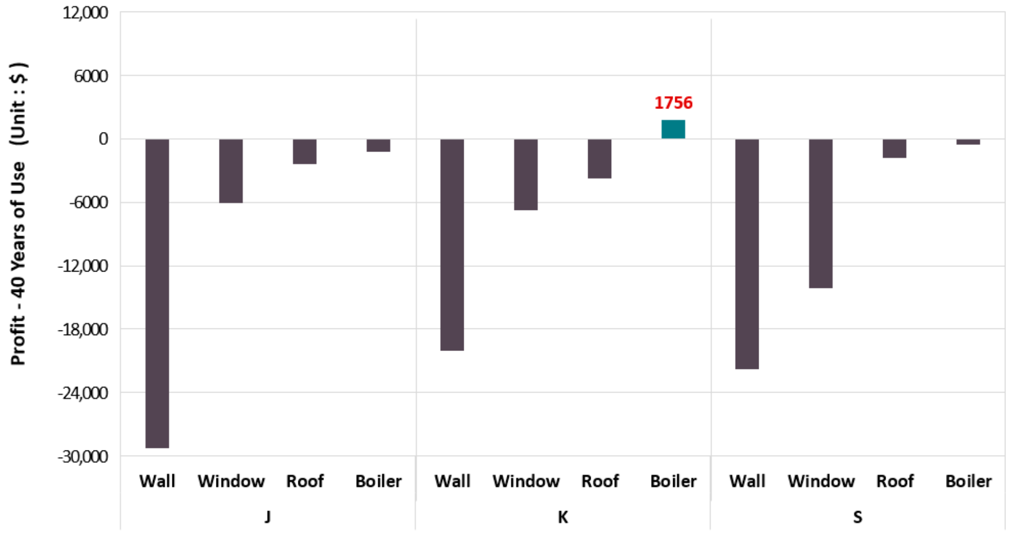


Figure 12. Result of analysis of economic feasibility of applying each improvement factor in the case of non-subsidized construction costs relating to welfare centers for the elderly.

In the case of improvement works, as shown in Figure 13, when only the net energy improvement cost is analyzed, such as when government support or remodeling work is mandatory, the S model's windows have the highest energy profit amount, followed by the J model's external wall insulation improvement work, which shows the next highest profit amount.

Therefore, when prioritizing the energy performance improvement factors for senior centers while considering the economic effects [59,60], it is suggested to make improvements according to the process shown in Figure 14. As described in Figure 14, the first step is to determine whether the construction is eligible for support and to identify the intended effects of the improvements. This process suggests that boiler improvements should be prioritized when considering the economic effects, if no support is available.

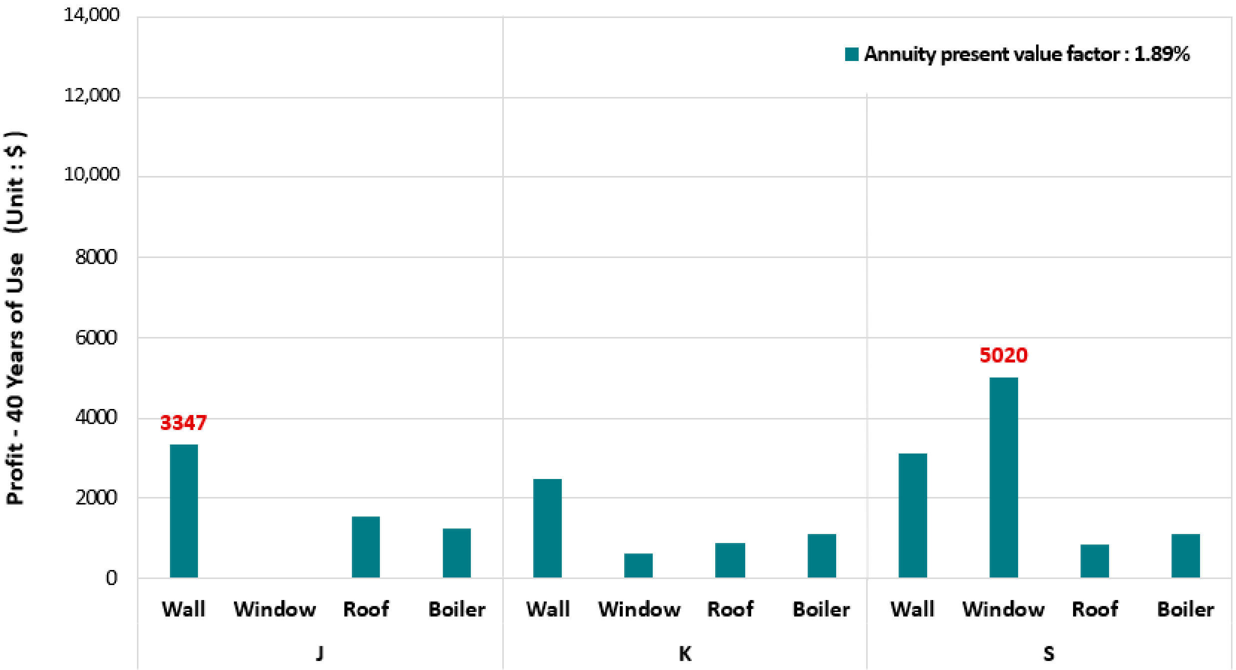


Figure 13. Results of economic analysis of the application of each improvement factor in senior centers when construction costs are subsidized.

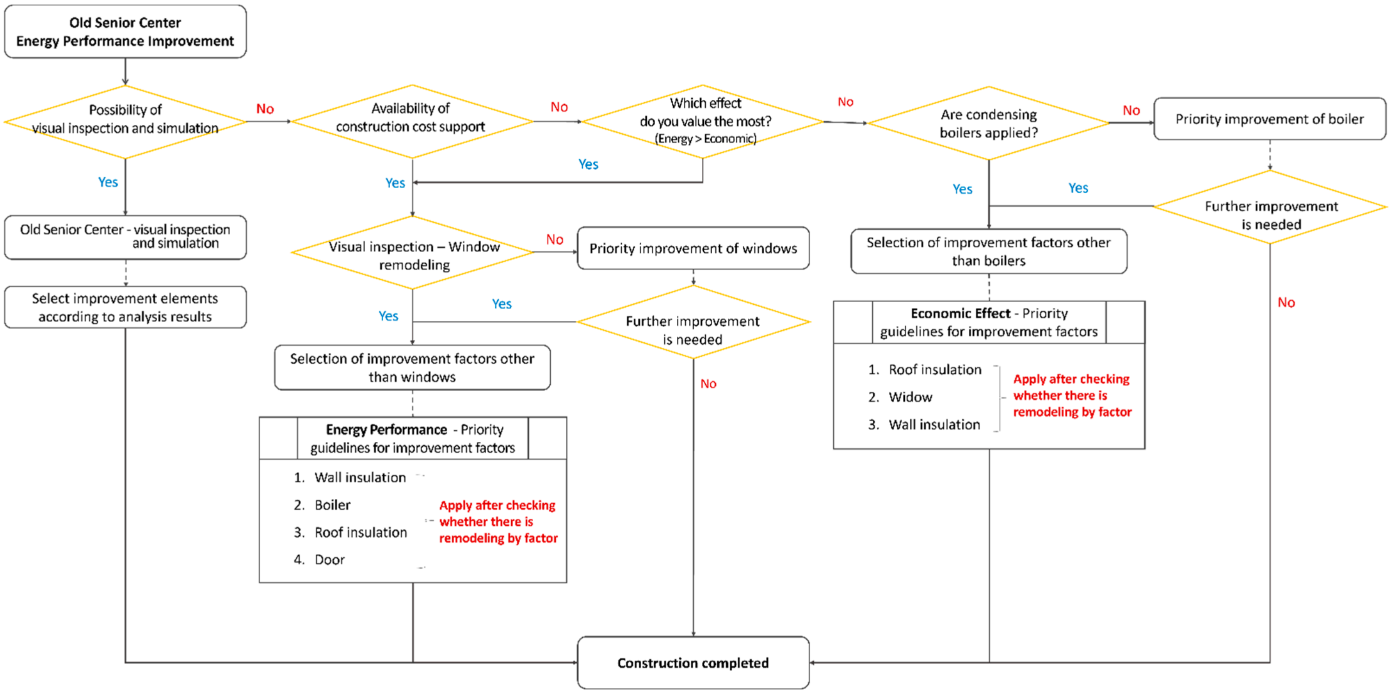


Figure 14. Energy performance improvement factor selection step considering energy improvement effects and economic improvement effects.

6. Discussion

This study evaluated energy performance improvements in aging senior centers by analyzing the impact of various building retrofits, with each element's energy-saving effects assessed through the ECO2 simulation tool. The results indicated the following average improvement rates in primary energy consumption: walls (25.9%), windows (8.0%), boilers (6.5%), roofs (6.0%), and doors (1.8%). These findings demonstrate the importance of enhancing building envelope components, particularly walls and windows, to achieve significant energy conservation.

After interpreting these findings, it becomes evident that retrofitting the walls and windows was the most effective measure in reducing energy consumption by minimizing heat loss, air infiltration, and maintaining stable indoor temperatures. Windows, in particular, proved crucial due to their potential for heat loss reduction, thus enhancing the overall energy efficiency. Boiler replacements also demonstrated considerable improvement in heating efficiency, reducing heating energy demands significantly. These results align with the previous research, which highlights the importance of building envelope retrofits in enhancing energy efficiency in facilities that serve elderly populations.

In terms of practical applications, this study provides a prioritized framework for energy performance improvements in senior centers and other aging public facilities. By indicating that windows and walls should be prioritized for maximum energy savings, this framework offers a practical guideline for facility retrofits within budget constraints. Economically, the 40-year life cycle analysis identified boiler replacements as the most cost-effective retrofit. When financial support is limited, focusing on boilers, followed by roof, window, and wall upgrades, could optimize returns based on operational cost reductions.

With government subsidies, the recommended prioritization shifts to windows, exterior walls, boilers, and roofs, leveraging the financial support to align with greenhouse gas reduction initiatives and maximize energy performance. Current government initiatives aimed at reducing carbon emissions present an ideal opportunity to implement comprehensive retrofits, particularly in building envelope improvements, to achieve substantial primary energy savings in senior centers.

There are some limitations to this study, particularly regarding data accuracy and scope. Due to a lack of preserved architectural records for many of the senior centers, the baseline insulation conditions were estimated based on the Building Act standards relevant to each building's construction year, which may limit precision. Additionally, variations in building configurations and material integrity were observed across the surveyed sites. Although the ECO2 simulations and blower door tests provided valuable insights, the lack of direct energy consumption data limited the accuracy of the projected energy savings. Future studies should integrate long-term energy monitoring systems to capture actual energy use before and after retrofits, thereby enhancing accuracy.

Further research could also consider the health-related outcomes of energy-efficient retrofits, such as indoor air quality improvements. Given that elderly residents spend extended time indoors, integrating systems like total heat exchangers could simultaneously improve air quality and energy efficiency, thereby enhancing resident health and comfort. Extending this study to various types of public facilities would also allow for a more comprehensive comparison of the energy performance improvements under different conditions.

In conclusion, this study provides a prioritized approach to retrofitting senior centers and other aging buildings, which can effectively achieve energy cost savings and carbon reduction goals. The findings highlight windows and walls as key components for energy efficiency and suggest that limited-budget retrofits should focus on maximizing the energy impacts by prioritizing these elements. This study serves as a practical reference for researchers and practitioners aiming to optimize energy improvements in aged facilities and emphasizes that renewing aged structures is essential, given both the environmental and economic imperatives. As such, this research contributes a foundational model that future studies can build upon to develop sustainable, energy-efficient strategies for aging buildings.

7. Conclusions

In this study, a current status survey was conducted, targeting 20 senior centers in the metropolitan area, and the energy performance improvement factors were selected via a literature review. An ECO2 simulation was performed to analyze the changes in energy consumption, and an economic analysis was performed for the J, K, and S standard models. Accordingly, a method for selecting the energy performance improvement factors was proposed.

Based on these findings, the main results of this study are as follows:

(1) As a result of the ECO2 simulation analysis, the following measures had the greatest effect on primary energy consumption, in descending order: outer walls, windows, boilers, roofs, and doors. The greatest effect for exterior wall improvements was observed in senior center D, and the average energy consumption improvement resulting from the application of PF boards was 25.9%.
(2) As a result of the ECO2 simulation analysis, the senior center with the greatest improvement effect relating to windows and doors was S, and the average improvement rate was 8% when low-e, double-glazed windows were installed.
(3) The standard models J, K, and S senior centers were selected based on the average type of floor area, energy demand, energy consumption, and primary energy consumption. For the energy consumption improvement effect of the performance improvement measures on the standard models, the effect of the outer wall improvements on model J was 11.0%, and the effect of the window and door improvements on model S was the greatest at 19.9%. For model K, the effect of outer wall improvement was the highest at 14.4%.
(4) A blower door test was conducted to verify the airtight performance of the buildings after the window improvements. According to the results of a calculation of the number of ventilations per hour, the α-senior center exhibited an improvement effect of 52.5%, which was about 35.2% higher than the simulation result. For the β-senior center, the improvement effect was about 4.6% lower than the 9.8% effect obtained in the simulation, but the effect of pressurization was similar to that obtained in the simulation.
(5) According to the results of the energy performance improvement effect analysis in this study, the improvement factors should be selected in the following order: windows, outer walls, boilers, roofs, and doors.
(6) As a result of the life cycle cost analysis of the heating costs over a 40-year period, the energy cost improvements of the J, K, and S standard models were the greatest after window improvements. However, in the life cycle cost analysis conducted by including the construction costs, only the boiler improvement of the K model generated a profit of USD 1756.
(7) According to the results of the economic feasibility analysis in this study, when carrying out improvement work without government support, priority should be given to improving the boiler, as it resulted in the lowest deficit.
(8) In recent years, construction costs have risen excessively, and it has been confirmed that some energy performance improvements are not economically feasible in terms of life cycle costs. However, due to the aging of buildings, renewal work has become a necessity rather than an option. When carrying out renewal work within a limited budget, it is expected that this study will serve as a reference for prioritizing areas for improvement by considering energy performance enhancements first.

In future research, we plan to measure energy consumption before and after the application of various improvement factors during the conversion of the existing senior centers into green buildings, with the aim of enhancing their energy performance. In addition, we plan to analyze the effects of installing a total heat exchanger, which is effective at improving indoor air quality and energy consumption in consideration of the health of the elderly, whose activities are restricted to indoor settings if the outdoor air is contaminated. Finally, the data were verified using confidential measurement data that affect heating energy consumption, rather than direct data on energy consumption. Therefore, a comparison with actual usage is limited.

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