

Article

Quantitative Analysis and Multi-Index Evaluation of the Green Building Envelope Performance in the Cold Area of China

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Abstract: In China, relevant standards about building energy efficiency and green buildings have resulted in corresponding requirements for the envelope thermal performance. However, improvement of the thermal performance of the envelope is accompanied by an increase of the environmental impact and cost. This study quantitatively analyzed the thermal performance, environmental impact, and cost of the green building envelope in cold areas and established a common practice database, as well as a multi-index evaluation model. The results show that the best thermal performance improvements are 40% in residential buildings and 30% in public buildings, respectively, based on the relevant standards. The exterior walls and windows have the greatest impact on building heat consumption. There is no significant correlation between the heat consumption and the comprehensive heat transfer coefficient of 10 green buildings. Therefore, the comprehensive heat loss coefficient is corrected. The verification results show that all errors except project 10 are within 15%. Additionally, the projects with balanced thermal performance improvement of exterior walls and windows showed a better performance. Finally, the best combination of residential building envelopes in the cold area was selected, using the evaluation model and quantitative database to calculate the comprehensive score.

Keywords: thermal performance; green building; building envelope; multi-index evaluation; comprehensive heat loss coefficient

1. Introduction

In recent years, energy and environmental issues have attracted worldwide attention. The construction industry accounts for 30% of the global primary energy consumption and also contributes to approximately one-third of global carbon emissions [1,2]. Global building energy consumption has been growing steadily due to rapid urbanization, climate change, and other drivers [3,4]. From 2000 to 2016, China's urbanization rate increased from 36% to 58%, resulting in considerable energy consumption and carbon emissions [5]. China's total CO₂ emissions in 2015 accounted for 30% of the world's total, and the country has thus become the world's largest CO₂ emitter [6]. In the same year, China submitted to United Nations Framework Convention on Climate Change (UNFCCC) an intention document determined by the state, promising to reach peak carbon dioxide emissions by 2030, which also posed a challenge to the construction sector. China's building energy consumption accounts for 21% of the total energy consumption [7], with significant potential for energy conservation and emission reductions. About two-thirds of China's regions are located in severely cold and cold regions with high heating demands in winter. The heating energy consumption of northern cities accounts for 40% of the total building energy consumption [8,9].

With the rapid development of China's building energy efficiency, relevant standards and specifications are also being constantly updated and developed. Based on the heating energy consumption in 1980, the first step of the residential building energy efficiency target of 1986 was to reduce the energy consumption by 30% [10], which has been developed to the fourth step of the energy efficiency target, with the aim of reducing energy consumption by 75% [11]. The latest standard (JGJ 26-2018) was officially implemented on 1 August 2019. The current standard of public buildings is the Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015) [12]. The first Assessment Standard for Green Building (GB/T 50378-2006) of China was implemented in 2006. The GB/T 50378-2019 [13] is the latest version, which was implemented on 1 August 2019. The thermal performance of a building envelope is the key factor influencing building energy consumption. Building energy efficiency standards [11,12] require the finite value of the heat transfer coefficient of the building envelope. The three levels in the Assessment Standard for Green Building [13] require the thermal performance of an enclosure to be improved by 5%, 10%, and 20%, respectively, based on the building energy efficiency standards [11,12].

Research on the improving thermal performance of the building envelope primarily focuses on optimization of the thermal insulation performance of exterior walls, exterior windows, and roofs. Life cycle assessment (LCA) is widely used in the optimal design of the building envelope [14,15]. Kaynakli [16] used the theory of LCA to optimize the thickness of external wall insulation under different heating modes. Dylewski [17] used the life cycle method to analyze the thickness of the economic insulation layer of external walls under the influence of different insulation materials and heat sources in Poland. Additionally, Daouas [18] considered the influence of sky radiation on the heat transfer of the roof, calculated the energy consumption of the roof by numerical simulation, and determined the economic thickness of different insulation materials of typical roofs in Turkey with the minimum life cycle cost as the optimization goal. Furthermore, Hee et al. [19] compared the building energy consumption of windows for different window-to-wall ratios. The result showed no significant difference in building energy consumption between 34% and 41% of the window-to-wall ratio. Single objective optimization usually takes the minimum life cycle cost or carbon emission as the optimization objective. Song et al. [20] used the economic net present value (NPV) method to evaluate different envelope modification methods. Zhang et al. [21] used energy consumption simulation software and the calculation model of life cycle cost analysis to analyze the influence rule of different material types and thicknesses of the thermal insulation layer on building energy consumption and conducted an economic analysis to optimize the thermal insulation layer of a university building envelope in Chengdu. Moreover, Doodoo et al. [22] analyzed the lowest comprehensive cost envelope in the life cycle of multistory buildings in southern Sweden, which can reduce the heating energy consumption of buildings by 28–43%. Additionally, Rahman Azari et al. [23] studied the influence of different thermal insulation materials, window types, and window-to-wall ratios (WWR) on the life cycle environment of an office building. Saafi et al. [24] comprehensively considered the roof structure, type of thermal insulation material, aging of thermal insulation materials, and roof reflectivity; used Energy Plus to simulate energy consumption; and determined the thickness of the economic thermal insulation layer of different forms of roofs in Tunisia. Li et al. [25] developed an assessment framework to analyze the impact of specific carbon on residential buildings. Furthermore, Fayez et al. [26] selected 13 cities in Australia and calculated the energy efficiency and carbon footprint of 15 kinds of wall insulation materials through simulation to obtain economic and reasonable insulation materials. Adamczyk et al. [27] proposed a method to evaluate the environmental and economic benefits and analyzed the selection of thermal insulation materials and thicknesses of the external walls of residential buildings. Azari et al. [28] used the multi-objective optimization algorithm to optimize the Seattle office building envelope. Global warming, acidification, eutrophication, smog formation, and ozone depletion were selected as indicators of the environmental impact. Kosareo and Ries [29] compared the effects of large green roofs and traditional roofs on ozone depletion, global warming, acidification, and eutrophication. Wu et al. [30] proposed a multi-objective optimization and transformation method

to optimize the envelope and energy system to reduce the greenhouse gas emissions of the entire community by 76%. In recent years, building simulation software and intelligent algorithms have been often used in the research of multi-objective optimization [31]. Maria Ferrara [32] used Transient System Simulation Tool (TRNSYS) to simulate the energy consumption of green buildings and considered it as the evaluation index to optimize the design of the enclosure through GenOpt. Ascione [33] used a genetic algorithm to carry out multi-objective optimization for building envelope design, proposed different optimization objectives for different private and public stakeholders, and formulated the best design strategy. Additionally, Ciulla et al. [34] used TRNSYS to simulate the energy consumption of non-residential buildings in Europe, and combined with a neural network, developed a building energy consumption prediction tool. Wu et al. [35] established the multi-objective optimization model of zero energy consumption buildings by combining multi-objective optimization technology with a comprehensive evaluation method. They used NSGA-II (non-dominated sorting genetic algorithm II) to optimize the enclosure with the goal of cost and energy consumption. Therefore, before selecting the optimization parameters, sensitivity analysis should be performed to select the parameters that have a greater impact on the optimization [36–38].

With the development of the Assessment Standard for Green Building and building energy efficiency standards, the requirements for thermal performances of the building envelope have gradually improved. However, only considering the thermal performance is against the concept of green building, the relevant standards pay too much attention to the improvement of thermal performance, and there are a lack of corresponding regulations and suggestions on the selection of enclosure materials. Whether improvement of the thermal performance of the building envelope can achieve good energy savings and economic and environmental benefits remains to be studied and analyzed. Many researchers have used building simulation software and optimization selection tools to optimize the specific building envelope structure with the thermal performance, cost, and environmental impact as objectives [31–35]. However, there is a lack of summary research on the practices of the green building envelope in different climate regions of China, and a corresponding multi-index evaluation system has not yet been formed. The thermal performance of the building envelope specified in relevant standards often corresponds to various methods. The application of multi-index evaluation tools can guide the formulation of building envelope schemes. Additionally, although the thermal performance of the green building envelope has been improved on the basis of ordinary buildings, the actual heat consumption in operation is affected by many factors, such as personnel operating habits, actual outdoor temperature changes, the matching of performance improvement between envelope structures, etc., which results in significant deviation between the actual heat consumption and the simulation calculation value. The entire thermal performance of an enclosure often deviates from the expectation. Therefore, this paper uses simulation, project measurement, quantitative analysis, and sensitivity analysis to study the relationship between the thermal performance and heat consumption of the green building envelope in cold areas and establishes a multi-index evaluation system, including a multi-index evaluation model and database of an envelope scheme, to guide the design and evaluation of the green building envelope.

2. Materials and Methods

This study presents a comprehensive analysis of the envelope of green buildings in cold areas and establishes a multi-index evaluation model. The method is divided into four parts. In the first part, typical public buildings and residential buildings are modeled to simulate the heating load and analyze the thermal performance of the envelope. The second part involves investigating the green building envelope in cold areas of China and performing a quantitative analysis of the thermal performance, environmental impact, and cost of different building envelope practices. The third part tests the heat consumption of green buildings in the cold area, analyzes the relationship between the thermal performance of the envelope and heat consumption, and corrects the comprehensive

heat loss coefficient. The fourth part establishes the multi-index evaluation model and proposes a decision-making method of envelope design.

2.1. Simulation of Building Heat Load

2.1.1. Energy Simulation Software

Energy Plus is a building energy consumption simulation software developed by the U.S. Department of Energy. It is a new generation of computing core without a user graphical interface. It inherits the features and functions of Blast and DOE-2 and optimizes the computing methods and program structure. Energy Plus uses a conduction transfer function (CTF) to calculate heat transfer, and the calculation result is more accurate. Moreover, it uses a modular system simulation method with a variable time step, and it is widely used in the field of building energy. Design Builder is a building energy consumption simulation software developed with Energy Plus as the core. It has a visual graphic interface which is more convenient to operate so it was selected as the simulation tool.

2.1.2. Building Model

The parameters of building models were determined according to the requirements of the *Design Standard for Energy Efficiency of Public Buildings* (GB 50189-2015) [12]. The parameters of residential buildings were determined according to the *Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones* (JGJ 26-2010) [39]. In order to simplify the modeling work, the two types of buildings adopt the same appearance and internal structure, as shown in Figure 1. The difference is in the building size and enclosure parameters, as shown in Table 1. And the building models are added in the Appendix A.

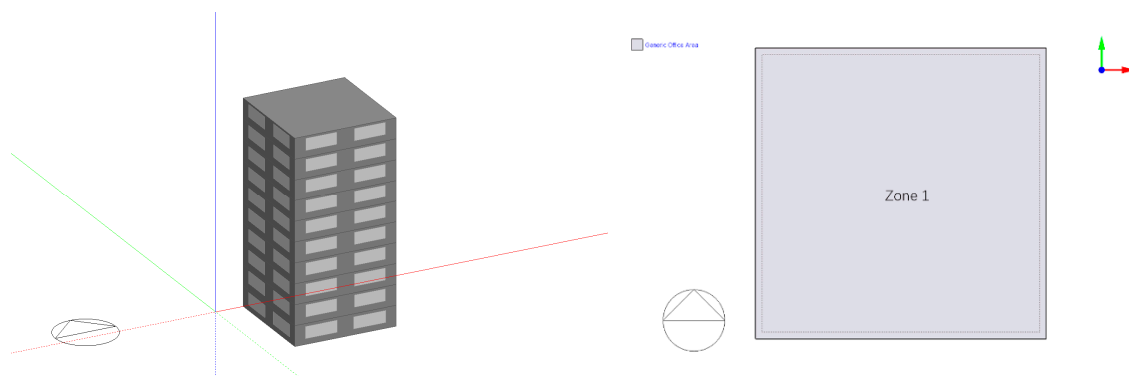


Figure 1. Building stereogram and plan of a typical building model.

Table 1. Building prototype modeling parameters in a cold area.

Building Type	Shape Coefficient	External Window U (W/m ² ·K)	External Wall U (W/m ² ·K)	Roof U (W/m ² ·K)	Window-Wall Ratio	Length (m) × Width (m) × Height (m)
Residential building	0.3	2.7	0.7	0.45	0.3	15 × 15 × 30
Public building	0.4	1.9	0.45	0.4	0.5	11 × 11 × 30

2.1.3. Quantification of the Thermal Performance of the Envelope

The heat transfer coefficient is calculated by setting the window type in Design Builder to quantify the thermal performance of the outer window, but the heat transfer coefficient of the outer window and roof is calculated using Equations (1)–(3):

$$R = \frac{\delta}{\lambda} \quad (1)$$

$$R_o = R_i + \sum R + R_e \quad (2)$$

$$U = \frac{1}{R_o}, \quad (3)$$

where R is the thermal resistance of each layer of material, $(\text{m}^2 \cdot \text{K})/\text{W}$; δ is the thickness of each layer of material, m ; λ is the thermal conductivity of each layer of material, $\text{W}/(\text{m} \cdot \text{K})$; R_o is the heat transfer resistance of the envelope, $(\text{m}^2 \cdot \text{K})/\text{W}$; R_i is the heat transfer resistance of the inner surface, $(\text{m}^2 \cdot \text{K})/\text{W}$; R_e is the heat transfer resistance of the outer surface, $(\text{m}^2 \cdot \text{K})/\text{W}$; and U is the heat transfer coefficient of the envelope, $\text{W}/(\text{m}^2 \cdot \text{K})$.

2.2. Measurement and Analysis of Building Heat Consumption

2.2.1. Investigation of the Envelope of Green Buildings

This part describes the investigation and analysis of materials and practices of the envelope structure of 20 green buildings in a cold area and presents a quantitative analysis of the thermal performance of typical building envelope practices.

2.2.2. Heat Consumption Test of Green Building Projects

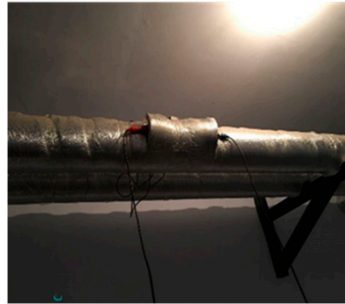
The basic information of ten green buildings in the tested cold area is shown in Table 2. In order to test the heat consumption of these buildings, we installed corresponding test instruments in the machine room. The electromagnetic flowmeter in Figure 2a was used to measure the total flow of a building's heating system. When selecting the test pipeline, the principle of stable flow and full pipe flow should be followed. Therefore, the backwater pipeline should be selected first, and the vertical trunk pipe should be selected as far as possible. When the length of the vertical trunk pipe is less than 1.5 meters, the horizontal trunk pipe can be selected, and the probes are arranged in a continuous straight place without an elbow, as shown in Figure 2b. After the probe is installed, adhesive tape is used to paste the insulation layer to reduce heat loss. Finally, parameters are set on the operating interface of the instrument, including the data recording duration, collection start time, data collection type, etc. There should be a stable power supply to ensure continuous power for the instrument during the test.

Table 2. Information of ten green buildings.

Project	Location	Type	Grade
1	Tianjin	Office	Three-star design
2	Tianjin	Office	Two-star operation
3	Shijiazhuang	Office	Three-star design
4	Tianjin	School	Three-star operation
5	Tianjin	Office	Three-star design
6	Tianjin	Office	Three-star operation
7	Tianjin	Office	Two-star design
8	Hezei	Residence	Three-star operation
9	Hezei	Residence	Three-star operation
10	Taian	Residence	Two-star operation



(a) Ultrasonic flowmeter.



(b) Probe arrangement of ultrasonic flowmeter.



(c) Temperature automatic recorder.

Figure 2. Heat consumption testing equipment.

The automatic temperature recorder in Figure 2c was used to measure the temperature of the water supply and return of the building heating system. First, parameters were set on the computer through the client-side to adjust the start and end recording time. The start time was consistent with the collection time of the above flow data, and the collection interval was set to once every 10 min. Thereafter, the two probes were placed inside the insulation layer of the supply and return water pipeline and fixed with tape. Based on the data of the aforementioned tests, the heat consumption of the building can be calculated according to Equations (1) and (2).

$$q_k = \frac{4.19 \times v \times (T_g - T_h) \times 600}{3.6 \times 1000000} \quad (4)$$

$$Q = \sum_{k=1}^n q_k \quad (5)$$

where 4.19 is the specific heat capacity of water; q_k is the heat consumption in 10 min, GJ; v is the speed of water flow, m^3/h ; T_g is the temperature of the inlet water, $^{\circ}\text{C}$; T_h is the temperature of the outlet water, $^{\circ}\text{C}$; and Q is the heat consumption of the entire heating season, GJ.

2.2.3. Comprehensive Heat Transfer Coefficient of the Envelope

The comprehensive heat transfer coefficient [40] represents the comprehensive thermal performance of the building envelope, and it can be seen from Equation (3) that it is only related to the heat transfer coefficient and area of the exterior wall, exterior window, and roof. The comprehensive heat transfer coefficient is introduced to explore the relationship between the actual heat consumption of green buildings and the performance of the envelope structure and whether the theoretical overall thermal performance of envelope can represent the actual thermal performance of the building envelope.

$$U_{Co} = \frac{U_{wall}A_{wall} + U_{roof}A_{roof} + U_{win}A_{win}}{A_{wall} + A_{roof} + A_{win}}, \quad (6)$$

where U_{Co} is the comprehensive heat transfer coefficient, $W/(m^2 \cdot K)$; U_{wall} is the heat transfer coefficient of the external wall, $W/(m^2 \cdot K)$; U_{win} is the heat transfer coefficient of the external window, $W/(m^2 \cdot K)$; U_{roof} is the heat transfer coefficient of the roof, $W/(m^2 \cdot K)$; A_{wall} is the area of the external wall, m^2 ; and A_{win} is the area of the external window, m^2 .

2.2.4. Comprehensive Heat Loss Coefficient of the Envelope

The building heat loss coefficient [41] is defined as the heat loss of the unit building area when the temperature difference between indoors and outdoors $\Delta t = 1$ K. The comprehensive heat loss coefficient adopted in this study is different from the previous concept in definition. It is related to the actual building heat consumption and building envelope area. It is defined according to Equations (7)–(9). The comprehensive heat loss coefficient calculated by the actual heat consumption and envelope area of the building implies the ultimate influence of the thermal performance, area, window-wall ratio, operation mode, and other factors on the heat consumption of the building envelope. The concept of the comprehensive heat loss coefficient of the envelope is introduced to represent the actual heat consumption of buildings, and the comprehensive heat loss coefficient is then optimized based on the measured data of building heat consumption and the heat transfer coefficient of external windows, external walls, and roofs, so as to establish a closer relationship between the thermal performance of the envelope and the actual heat consumption of buildings.

$$k_z = \frac{\bar{Q}}{A_w \times (T_{in} - T_{out})} \quad (7)$$

$$\bar{Q} = \frac{10^6 \times Q}{3.6 \times N \times 24} \quad (8)$$

$$A_w = A_{wall} + A_{roof} + A_{win}, \quad (9)$$

where \bar{Q} is the average building heat consumption, W; Q is the total heat consumption of the building heating season, GJ/a; N represents the heating days in winter; and A_w is the area of the external wall, m^2 .

2.3. Sensitivity Analysis

Sensitivity analysis primarily studies the contribution of one variable change to another variable change. In the process of the study, other parameters are fixed and only independent variables are changed to observe their influence on dependent variables. Relevant research shows that the change of energy consumption of building calculation after changing some design parameters is significantly larger than other parameters. Therefore, it is said that the sensitivity of these parameters is higher, so more attention should be paid to the design process and specifications. In order to accurately describe the sensitivity of a single variable to another variable, the sensitivity coefficient has been

used as an evaluation index in this study, which is calculated according to Equation (10). We used the dimensionless form of change of the input and output variables in the formula.

$$IC = \frac{OP \text{ change}\%}{IP \text{ change}\%}, \quad (10)$$

where IC is the sensitivity coefficient, IP is the input variable, and OP is the output variable.

The relationship between the factors influencing the comprehensive heat loss coefficient of the envelope is complex, and the existing analysis theory is not sufficient to establish the analytic function relation model in line with the actual situation. Therefore, we took the field measurement project in the cold region as an example and used the Design Builder for simulation, analyzing the change of comprehensive heat loss coefficient by changing the input quantity of envelope parameters. The energy consumption model is based on projects 1 and 10, as shown in Figures 3 and 4. And the building models are added in the Appendix A.

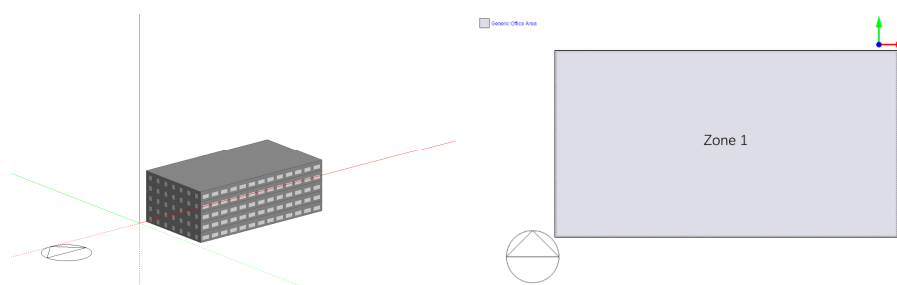


Figure 3. Building stereogram and plan of the model for project 1.

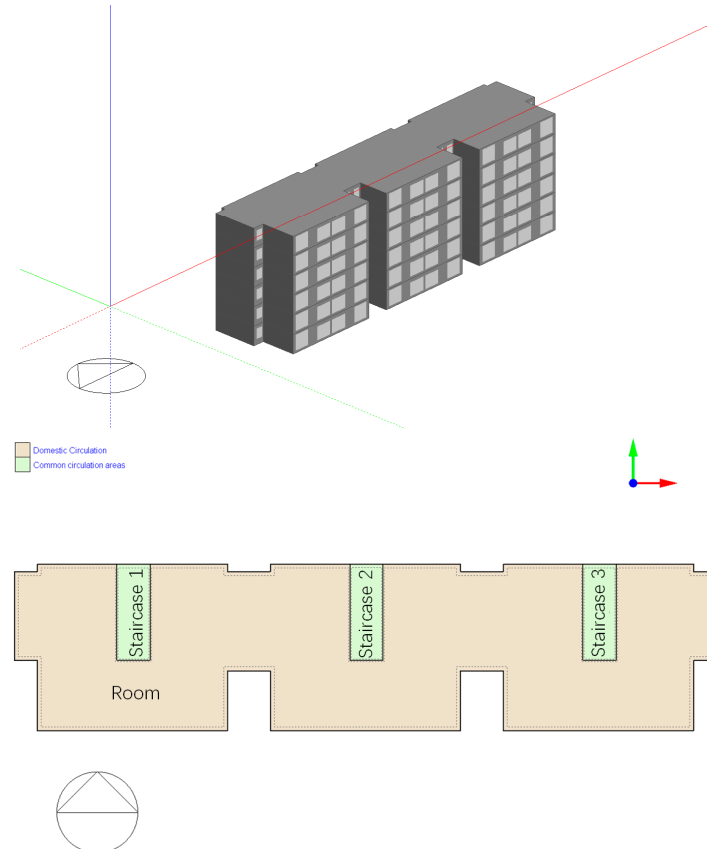


Figure 4. Building stereogram and plan of the model for project 10.

2.4. Life Cycle Assessment (LCA) and Cost Analysis

2.4.1. Life Cycle Assessment (LCA)

LCA is used to study the energy consumption and environmental impact of the building's life cycle. There are five common types of environmental impacts of building materials: non-renewable resource consumption (ADP), non-renewable energy consumption (PED), greenhouse effect (GWP), acidification effect (AP), and eutrophication (EP). This study focuses on energy consumption and the resulting carbon dioxide emissions. Therefore, PED and GWP were selected as environmental impact assessment indicators for green building envelope materials, and a quantitative analysis of different building envelopes was conducted. Tables 3 and 4 present the unit environmental impact equivalents of different types of insulation layer and external window with a 50-year cycle, respectively. According to the data, the environmental impacts of different building envelope practices were quantified.

Table 3. Non-renewable energy consumption (PED) and greenhouse effect (GWP) of different types of insulation layer [42] (pp. 90–95).

Material	PED (kgce/kg)	GWP (kg CO ₂ eq/kg)
Rock wool	2.6	5.02
Polyurethane (PU)	6.74	11.5
Polystyrene (EPS/XPS)	8.46	12.1

Table 4. PED and GWP of different types of external window [42] (pp. 117–120).

Frame	Glass	PED (kgce/m ²)	GWP (kg CO ₂ eq/m ²)
PVC	5low-e + 12Ar + 5	4.51	9.89
Heat broke aluminum	5low-e + 6A + 5	6.73	15.25
Heat broke aluminum	5low-e + 8A + 5	6.73	15.25
Heat broke aluminum	5low-e + 6Ar + 5	6.73	15.25
Heat broke aluminum	5low-e + 12A + 5	6.73	15.25
Heat broke aluminum	5low-e + 13Ar + 5	6.73	15.25
PVC	5low-e + 12A + 5 + 12A + 5	5.31	11.7
PVC	5low-e + 10Ar + 5 + 6Ar + 5	5.31	11.7
PVC	5low-e + 10Ar + 5 + 8Ar + 5	5.31	11.7
PVC	5low-e + 13Ar + 5 + 13Ar + 5	5.31	11.7

2.4.2. Cost Analysis

In addition to improving the thermal performance and reducing the environmental impact, the design of the green building envelope needs to pay attention to reducing the economic costs. We obtained the material prices from the China Building Material Online Website [43]. Tables 5 and 6 summarize the unit prices of the insulation layer and window types, respectively. According to the data, the costs of different building envelope practices can be quantified.

Table 5. Costs of different types of insulation layer.

Material	Unit Price (RMB/m ³)
Rock wool	302
Polyurethane	680
Polystyrene (EPS/XPS)	348/501

Table 6. Costs of different types of external window.

Frame	Glass	Unit Price (RMB/m ²)
PVC	5low-e + 12Ar + 5	359
Heat broke aluminum	5low-e + 6A + 5	450
Heat broke aluminum	5low-e + 8A + 5	474
Heat broke aluminum	5low-e + 6Ar + 5	613
Heat broke aluminum	5low-e + 12A + 5	568
Heat broke aluminum	5low-e + 13Ar + 5	650
PVC	6low-e + 12A + 6 + 12A + 6	483
PVC	6low-e + 10Ar + 6 + 6Ar + 6	495
PVC	6low-e + 10Ar + 6 + 8Ar + 6	512
PVC	6low-e + 13Ar + 6 + 13Ar + 6	540

2.5. Multi-Index Evaluation

The method of using multiple indexes to evaluate an object is known as multi-index evaluation. The basic idea is to transform multiple indicators into one indicator that can reflect the comprehensive situation for evaluation. Improvement of the thermal performance of the building envelope is often accompanied by an increase of the cost and environmental load. To measure the quality of the building envelope, we should not only focus on the thermal performance, but also evaluate the practice of the building envelope from multiple perspectives. Therefore, this study established a multi-index evaluation model, Equation (11), and selected the heat transfer coefficient, cost, non-renewable energy consumption (PED), and greenhouse effect (GWP) as indicators from the aspects of the environment, cost, and thermal performance, to evaluate the green building envelope in a cold area. The indexes of different enclosures are quantized and dimensionless and the corresponding database was obtained. The multi-index evaluation model combined with the database was used to evaluate and select the best green building envelope.

$$Z = \omega_1 \overline{U} + \omega_2 \overline{\text{PED}} + \omega_3 \overline{\text{GWP}} + \omega_4 \overline{\text{COST}}, \quad (11)$$

where Z is the comprehensive score, ω_i is the weight value of each index, \overline{U} is the dimensionless index of the Heat Transfer Coefficient, $\overline{\text{PED}}$ is the dimensionless index of non-renewable energy consumption, $\overline{\text{GWP}}$ is the dimensionless index of the greenhouse effect, and $\overline{\text{COST}}$ is the dimensionless index of cost.

3. Analysis

3.1. Heat Consumption Simulation

3.1.1. Residential Building

The simulation results of the winter heat consumption of residential buildings in cold regions are shown in Table 7. When the thermal performance of the building envelope is improved by 65%, close to the nZEB level, the heat load per unit area decreases by 22.23 kWh/m². Figure 5, drawn from Table 7, reflects the relationship between the thermal performance and heat consumption of residential buildings in cold regions, which can be expressed by a polynomial equation. It can be seen that when the thermal performance of the enclosure is improved by less than 40%, the building energy consumption decreases significantly; when the lifting range is more than 40%, the decreasing rate of the thermal load slows down significantly.

Table 7. Heat load of a prototype residential building.

Improvement	U-Value(W/m ² ·K)			Heat Load (kWh/m ² ·a)	Heat Load Decrease (kWh/m ² ·a)	Decline Rate
	External Window	External Wall	Roof			
0%	2.7	0.7	0.45	41.02	N/A	N/A
5%	2.57	0.67	0.43	38.57	2.45	5.97%
10%	2.43	0.63	0.41	35.18	3.39	8.79%
20%	2.16	0.56	0.36	31.73	3.45	9.81%
30%	1.89	0.49	0.315	27.72	4.01	12.64%
40%	1.62	0.42	0.27	23.02	4.7	16.96%
50%	1.35	0.35	0.225	20.56	2.46	10.69%
60%	1.08	0.28	0.18	19.99	0.57	2.77%
65%	0.95	0.25	0.16	19.86	0.13	0.65%

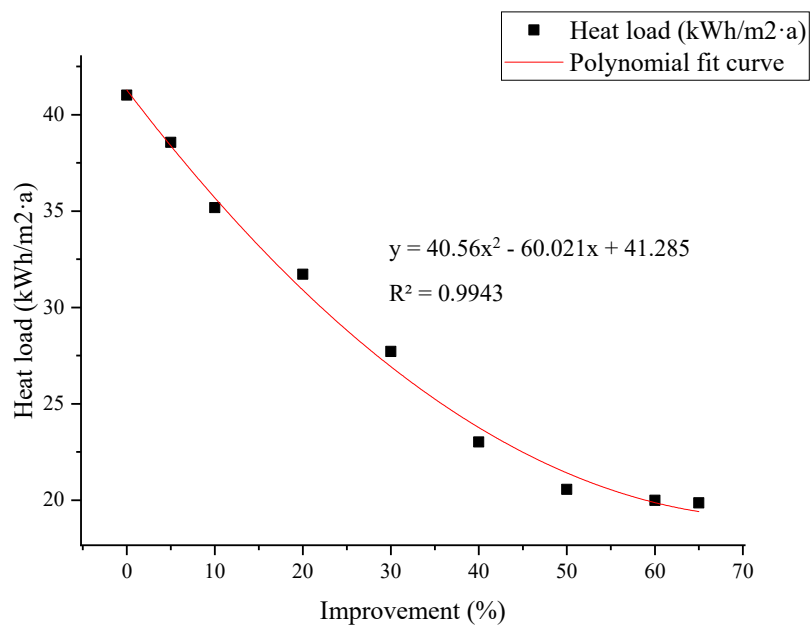
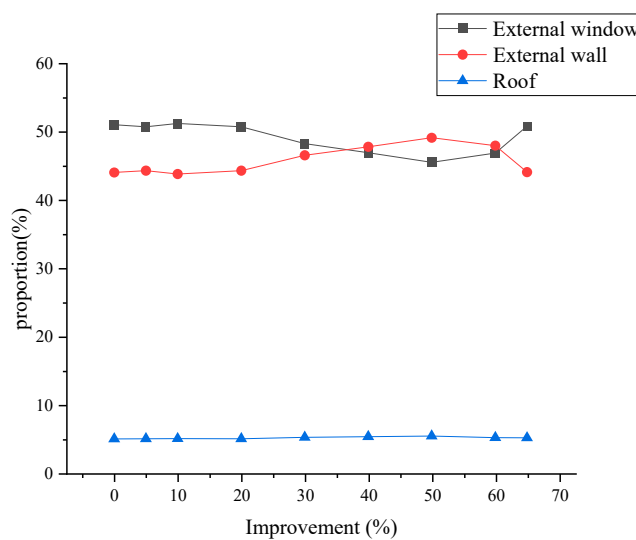
**Figure 5.** Relationship between thermal performance improvement and the heat load of a residential building.

Table 8 and Figure 6 show the proportion of heat load in each part of the residential building envelope in the cold area. The heat load formed by the external window was the highest at the beginning, accounting for 51.02%. With the gradual improvement of the thermal performance of the external window, its proportion began to decline, and the proportion of the outer wall began to increase. When the thermal performance is improved by 40%, the proportion of heat load of the external wall reaches the highest value of 47.8% and that of the external window is 46.92%. When the thermal performance reaches the standard of nZEB, the proportion of external window is 50.81% and that of the external wall is 44.08%. The proportion of heat load on the roof fluctuates from 4.95% to 5.38%. The average values were 49.12%, 45.77%, and 5.11%, respectively.

Table 8. Proportion of heat load in each part of the residential building envelope.

Improvement	External Window		External Wall		Roof	
	Heat Load (kWh/m ² ·a)	Proportion	Heat Load (kWh/m ² ·a)	Proportion	Heat Load (kWh/m ² ·a)	Proportion
0%	20.93	51.02%	18.06	44.03%	2.03	4.95%
5%	20.07	50.73%	17.52	44.29%	1.97	4.97%
10%	18.52	51.20%	15.85	43.80%	1.81	5.00%
20%	16.60	50.71%	14.50	44.30%	1.63	4.98%
30%	14.35	48.27%	13.83	46.54%	1.54	5.20%
40%	12.21	46.92%	12.44	47.80%	1.37	5.28%
50%	10.40	45.51%	11.22	49.11%	1.23	5.38%
60%	9.63	46.88%	9.85	47.97%	1.06	5.14%
65%	9.50	50.81%	8.24	44.08%	0.95	5.11%

**Figure 6.** Proportion of heat load in each part of the residential building envelope.

3.1.2. Public Buildings

The calculation results of the heat transfer coefficient and heat load of the public building envelope in a cold area are shown in Table 9. When the thermal performance is increased by 65%, the heat load per unit area decreases by 31.51 kWh/m². Compared to residential buildings, public buildings have greater energy saving potential. It can be seen from Figure 7 that the change trend of heat load with the improvement of thermal performance is consistent with that of residential buildings. When the thermal performance of the enclosure is improved by less than 30%, the building energy consumption is significantly reduced. When the lifting range is more than 30%, the decreasing rate of the thermal load slows down significantly. When the lifting range is more than 50%, the thermal performance of the envelope has little effect on the heat load.

Table 9. Heat load of a prototype public building.

Improvement	U-Value (W/m ² ·k)			Heat Load (kWh/m ² ·a)	Heat Load Decrease (kWh/m ² ·a)	Decline Rate
	External Window	External Wall	Roof			
0%	1.9	0.45	0.4	57.07	N/A	N/A
5%	1.8	0.428	0.38	51.92	5.15	9.02%
10%	1.71	0.405	0.36	46.63	5.29	10.19%
20%	1.52	0.36	0.32	41.27	5.36	11.49%
30%	1.33	0.315	0.28	34.45	6.82	16.53%
40%	1.14	0.27	0.24	30.53	3.92	11.38%
50%	0.95	0.225	0.2	27.41	3.12	10.22%
60%	0.76	0.18	0.16	25.66	1.75	6.38%
65%	0.7	0.16	0.14	25.57	0.09	0.35%

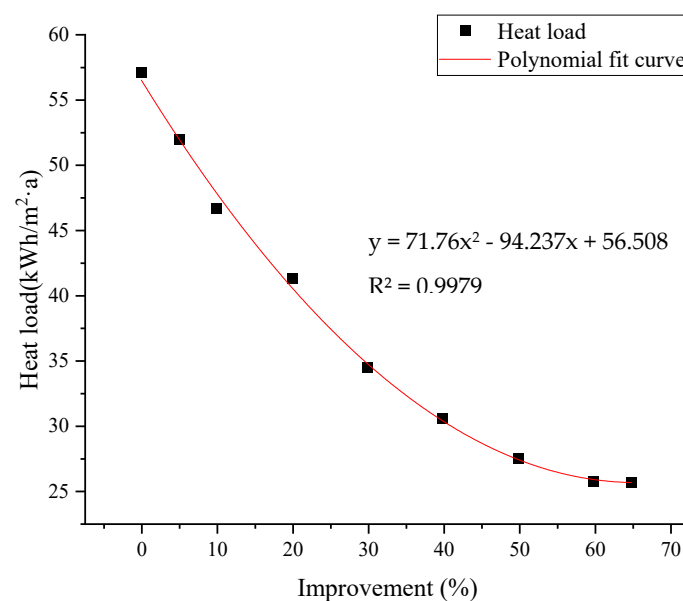


Figure 7. Relationship between thermal performance improvement and the heat load of a public building.

Table 10 and Figure 8 show the proportion of heat load in each part of the public building envelope in a cold area. The proportion of load in the three parts fluctuates within a certain range. The proportion of load in the outer window is 64.11–72.18%, the outer wall is 24.14–31.26%, and the roof is 3.68–4.87%. The average values are 69.10%, 26.80%, and 4.10%, respectively.

Table 10. Proportion of heat load in each part of the public building envelope.

Improvement	External Window		External Wall		Roof	
	Heat Load (kWh/m ² ·a)	Proportion	Heat Load (kWh/m ² ·a)	Proportion	Heat Load (kWh/m ² ·a)	Proportion
0%	41.19	72.18%	13.78	24.14%	2.10	3.68%
5%	38.17	70.79%	13.70	25.40%	2.05	3.81%
10%	37.48	71.22%	13.18	25.05%	1.96	3.73%
20%	33.86	70.13%	12.54	25.98%	1.87	3.88%
30%	25.49	67.71%	10.56	28.06%	1.59	4.23%
40%	21.50	66.10%	9.44	29.03%	1.59	4.87%
50%	18.22	64.11%	8.88	31.26%	1.31	4.63%
60%	18.84	68.61%	7.50	27.33%	1.11	4.05%
65%	18.15	71.01%	6.38	24.95%	1.03	4.04%

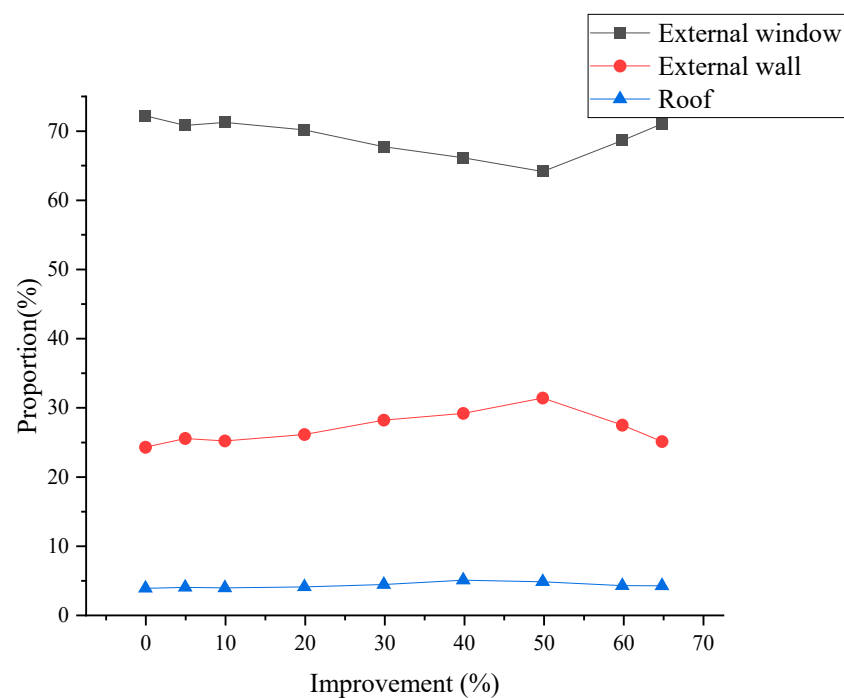


Figure 8. Proportion of heat load in each part of the public building envelope.

The range of thermal performance improvement of the enclosure structure should be kept reasonable. If blindly meeting the requirements of the nZEB standard, the building energy efficiency is not the best. In all the simulated prototype buildings, the proportion of heat load in each part of the building envelope is the external window > external wall > roof. It is evident that the external window and the external wall can be used as the key research objects of energy saving work, while the energy saving potential of the roof is low.

3.2. Building Envelope

3.2.1. Investigation of Envelope Practices of Green Buildings in Cold Areas

From an investigation of the enclosure structure of 20 green buildings in cold areas, the common practices of exterior walls, roofs, and windows were summarized. Their respective proportions are shown in Figure 9. Among the exterior wall construction materials, rock wool is the main choice of insulation layer, accounting for 35%, followed by PU board, accounting for 20%; XPS board and EPS board represent 15% of the materials. Aerated concrete block is the primary foundation material of green building exterior walls in cold areas, accounting for 80%. The primary choice of thermal insulation materials for roofing construction is XPS board, with a proportion of 35%, and the secondary type is rock wool, accounting for 20%. The outer window type is always a hollow glass type, with double-glazed windows accounting for 80% and triple-glazed windows accounting for 20%. The commonly used thickness of filled walls in green buildings is 200 mm. The average thickness of the external wall insulation layer is 85 mm. The minimum thickness of the roof insulation layer is 60 mm, the maximum is 300 mm, and the average thickness is 110 mm.

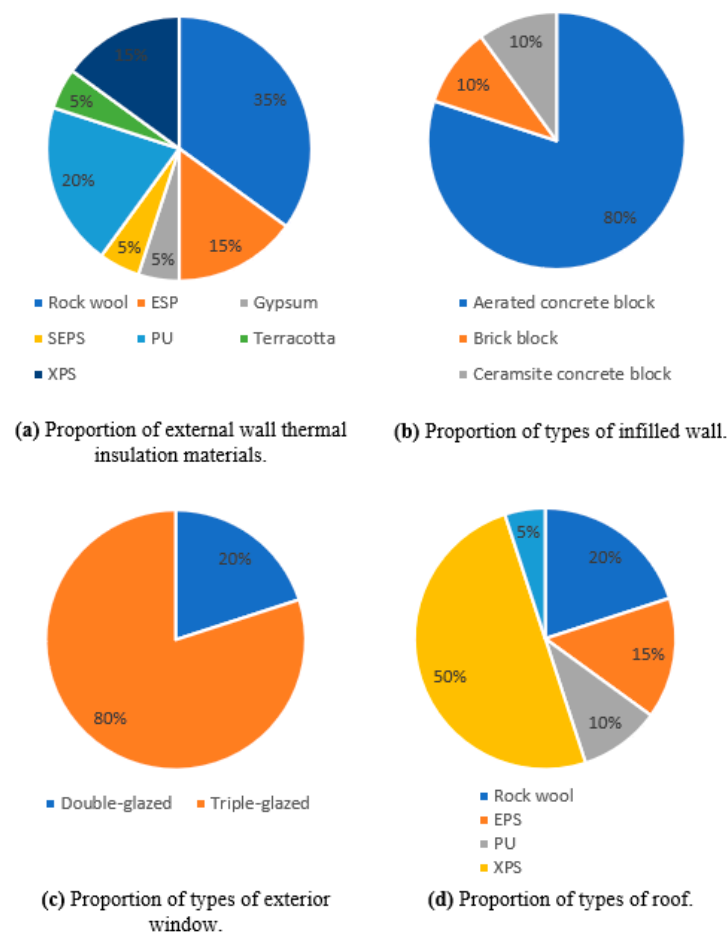


Figure 9. Proportion of building envelope materials.

Rock wool, PU slab, EPS slab, and XPS slab are commonly used as thermal insulation materials for green buildings in cold regions; aerated concrete block is used as outer wall foundation material; and reinforced concrete is used as floor foundation material. Common practices are shown in Table 11.

Table 11. Common practices of non-transparent envelopes.

Position	Inner Layer	Foundation Layer	Leveling Course	Insulation Layer	Outer Layer
Wall	Cement mortar	Aerated concrete block	Cement mortar	Rock wool/PU/EPS/XPS	Cement mortar
Roof	Cement mortar	Aerated concrete block	Cement mortar	Rock wool/PU/EPS/XPS	Cement mortar

3.2.2. Quantitative Analysis of the Thermal Performance of an Envelope

Based on the aerated concrete wall with a thickness of 200 mm and reinforced concrete floor with a thickness of 100 mm, the thermal performance of a non-transparent envelope structure was quantified and the corresponding heat transfer coefficient was obtained. Tables 12 and 13 present the quantitative results of the thermal performance of exterior walls and roofs with rock wool as insulation material, respectively.

Taking residential buildings in cold areas as an example, a quantitative study of the thermal performance improvement of an envelope structure was carried out. The initial U-values of the exterior wall and roof were $0.7 \text{ W/m}^2\cdot\text{k}$ and $0.45 \text{ W/m}^2\cdot\text{k}$, respectively.

Tables 14 and 15 show the level of thermal performance improvement for different insulation exterior walls and roofs. The thermal insulation layer with a 10 mm thickness can significantly improve the thermal performance of the external wall, with an increase of more than 20%. However, the roof needs a PU board of at least a 60 mm thickness to improve thermal performance.

Table 12. Quantification of the heat transfer coefficient of a rock wool insulation exterior wall.

Material	Thickness mm	Thermal Conductivity W/m·K	U-Value W/m ² ·K
Rock wool	10	0.041	0.528
	20	0.041	0.468
	40	0.041	0.381
	60	0.041	0.321
	80	0.041	0.278
	100	0.041	0.244
	120	0.041	0.218
	140	0.041	0.197
	160	0.041	0.180
	180	0.041	0.166
	200	0.041	0.153
Cement mortar	20	0.93	N/A
Aerated concrete block	200	0.14	N/A

Table 13. Quantification of the heat transfer coefficient of a rock wool insulation roof.

Material	Thickness mm	Thermal Conductivity W/m·K	U-Value W/m ² ·K
Rock wool	10	0.041	1.91
	20	0.041	1.30
	40	0.041	0.80
	60	0.041	0.57
	80	0.041	0.45
	100	0.041	0.37
	120	0.041	0.31
	140	0.041	0.27
	160	0.041	0.24
	180	0.041	0.21
	200	0.041	0.19
Cement mortar	20	0.93	N/A
Reinforced concrete	100	1.74	N/A

Table 14. Level of thermal performance improvement for different insulation exterior walls.

Thickness (mm)	Thermal Performance Improvement			
	Rock wool	PU	EPS	XPS
10	24.61%	30.91%	26.89%	28.01%
20	33.21%	42.50%	36.71%	38.36%
40	45.61%	56.94%	50.11%	52.13%
60	54.13%	65.59%	58.82%	60.87%
80	60.34%	71.34%	64.95%	66.91%
100	65.07%	75.44%	69.48%	71.34%
120	68.79%	78.52%	72.98%	74.72%
140	71.80%	80.91%	75.76%	77.39%
160	74.28%	82.83%	78.02%	79.55%
180	76.35%	84.39%	79.90%	81.33%
200	78.12%	85.69%	81.48%	82.83%

Table 15. Level of thermal performance improvement for different insulation roofs.

Thickness mm	Insulating Layer Material			
	Rock Wool	PU	EPS	XPS
10	N/A	N/A	N/A	N/A
20	N/A	N/A	N/A	N/A
40	N/A	N/A	N/A	N/A
60	N/A	20.06%	N/A	2.53%
80	0.40%	38.50%	17.82%	24.58%
100	18.27%	50.02%	32.87%	38.50%
120	30.70%	57.91%	43.26%	48.08%
140	39.85%	63.65%	50.86%	55.08%
160	46.87%	68.01%	56.67%	60.41%
180	52.42%	71.44%	61.25%	64.61%
200	56.92%	74.20%	64.95%	68.01%

As shown in Figure 10, the thermal performance of a rock wool exterior wall and the thickness of the insulation layer present a quadratic polynomial function relationship. It is apparent that when the thickness of rock wool reaches 140 mm, the thermal performance improvement rate of the external wall begins to slow down.

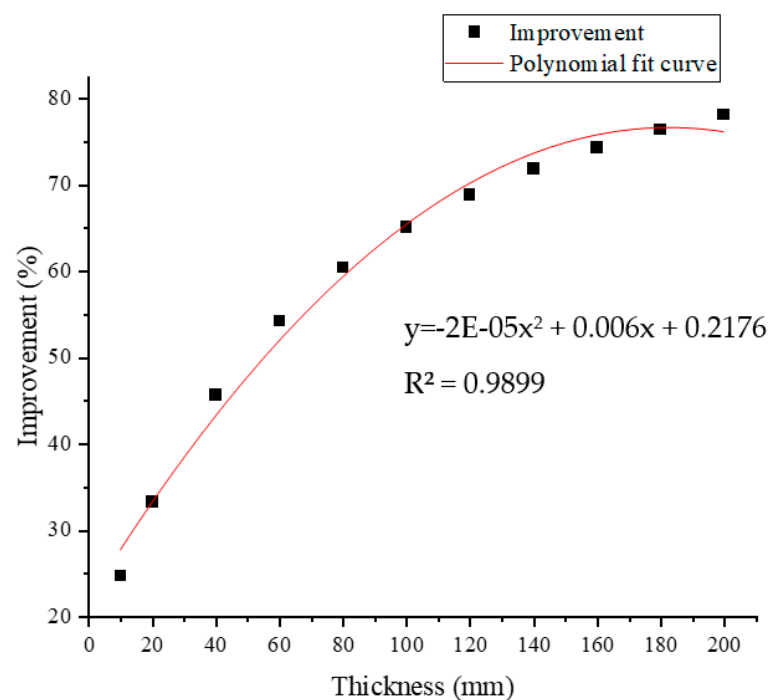
**Figure 10.** Relationship between the thickness of a rock wool insulation layer and the thermal performance of an exterior wall.

Figure 11 shows the relationship between the thermal performance of rock wool roofing and the thickness of the insulation layer. From the trend of curve change, it is evident that when the rock wool thickness reaches 230 mm, the thermal performance improvement rate of the roof begins to stabilize.

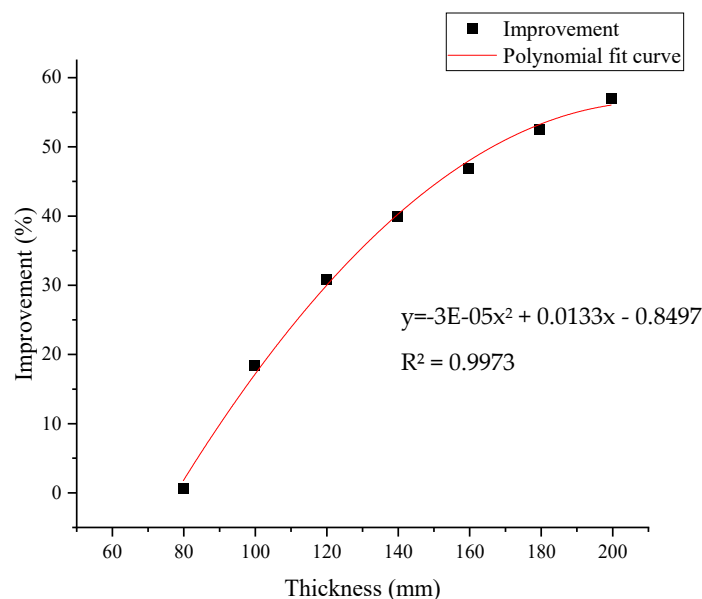


Figure 11. Relationship between the thickness of a rock wool insulation layer and the thermal performance of a roof.

The thermal performance of a transparent enclosure is not only related to window frame materials, glass types, and other components, but is also affected by the structure of the window frame, filling gas, hollow thickness, and other factors. The common window frames of green buildings are usually PVC or heat broke aluminium alloy. Additionally, 5 mm thick transparent glass and 5 mm thick Low-E thin film glass are usually used. The filling gas is primarily air and argon and the interlayer thickness range is 6–13 mm. In this study, the heat transfer coefficient of the outer window was calculated using the calculation function of the design Builder software and the different parameter combinations which affect the thermal performance of the outer window were input; the heat transfer coefficients of each combination were calculated. Taking a prototype residential building in a cold area as an example, the initial heat transfer coefficient of the outer window is 2.7 W/m²·k. The thermal performance improvement of each type of outer window was calculated, and the results are shown in Table 16.

Table 16. Improvement in the thermal performance of different types of windows.

Frame	Glass	U-Value W/(m ² ·k)	Improvement	
			Residential	Public
PVC	5 + 12Ar + 5	2.511	7.00%	N/A
Heat broke aluminum	5low-e + 6A + 5	2.43	10.00%	N/A
Heat broke aluminum	5low-e + 8A + 5	2.1	22.22%	N/A
Heat broke aluminum	5low-e + 6Ar + 5	1.988	26.37%	N/A
Heat broke aluminum	5low-e + 12A + 5	1.774	42.87%	6.63%
Heat broke aluminum	5low-e + 13Ar + 5	1.495	44.63%	21.32%
PVC	5low-e + 12A + 5 + 12A + 5	1.3	51.85%	31.58%
PVC	5low-e + 10Ar + 5 + 6Ar + 5	1.2	55.56%	36.84%
PVC	5low-e + 10Ar + 5 + 8Ar + 5	1.13	58.15%	40.53%
PVC	5low-e + 13Ar + 5 + 13Ar + 5	1.06	60.74%	44.21%

3.2.3. Quantitative Analysis of the Environmental Impact and Costs of an Envelope

According to the environmental impact of the thermal insulation materials of the envelope in Table 3, the environmental impact of the four thermal insulation layers with different thicknesses was quantified. The results are shown in Tables 17 and 18. Quantitative indicators of the environmental impact of different types of windows are summarized in Table 4.

Table 17. PED of the thermal insulation layer.

Thickness mm	PED (kgce/m ²)			
	Rock Wool	PU	EPS	XPS
10	2.860	2.359	1.692	2.961
20	5.720	4.718	3.384	5.922
40	11.440	9.436	6.768	11.844
60	17.160	14.154	10.152	17.766
80	22.880	18.872	13.536	23.688
100	28.600	23.590	16.920	29.610
120	34.320	28.308	20.304	35.532
140	40.040	33.026	23.688	41.454
160	45.760	37.744	27.072	47.376
180	51.480	42.462	30.456	53.298
200	57.200	47.180	33.840	59.220

Table 18. GWP of the thermal insulation layer.

Thickness mm	GWP (kg CO ₂ eq/m ²)			
	Rock Wool	PU	EPS	XPS
10	5.522	4.025	2.420	4.235
20	11.044	8.050	4.840	8.470
40	22.088	16.100	9.680	16.940
60	33.132	24.150	14.520	25.410
80	44.176	32.200	19.360	33.880
100	55.220	40.250	24.200	42.350
120	66.264	48.300	29.040	50.820
140	77.308	56.350	33.880	59.290
160	88.352	64.400	38.720	67.760
180	99.396	72.450	43.560	76.230
200	110.440	80.500	48.400	84.700

Taking the prototype residential building in a cold area as an example, the environmental impact of the rock wool insulation exterior wall and roof under different thickness of insulation layer was analyzed. The initial heat transfer coefficients of external walls and roofs are 0.7 and 0.45 W/(m²·K) and the results are shown in Table 19. As the thickness of rock wool increases, the thermal performance of exterior walls and roofs gradually improves and the environmental impact indicators also increase. Therefore, the relationship between thermal performance improvement and the environmental impact was quantitatively analyzed.

Table 19. Thermal performance and environmental impact of a rockwool exterior wall and roof.

Thickness mm	Exterior Wall		Roof		PED/m ²	GWP/m ²
	U-Value W/(m ² ·K)	Improvement	U-Value W/(m ² ·K)	Improvement		
10	0.53	24.61%	1.91	N/A	2.86	5.522
20	0.47	33.21%	1.30	N/A	5.72	11.044
40	0.38	45.61%	0.80	N/A	11.44	22.088
60	0.32	54.13%	0.57	N/A	17.16	33.132
80	0.28	60.34%	0.45	0.40%	22.88	44.176
100	0.24	65.07%	0.37	18.27%	28.6	55.22
120	0.22	68.79%	0.31	30.70%	34.32	66.264
140	0.20	71.80%	0.27	39.85%	40.04	77.308
160	0.18	74.28%	0.24	46.87%	45.76	88.352
180	0.17	76.35%	0.21	52.42%	51.48	99.396
200	0.15	78.12%	0.19	56.92%	57.2	110.44

As shown in Figure 12, when the thermal performance of a rock wool insulation exterior wall is improved within 60%, the environmental impact index changes slowly. When the increase is greater than 60%, the change rates of PED and GWP begin to increase.

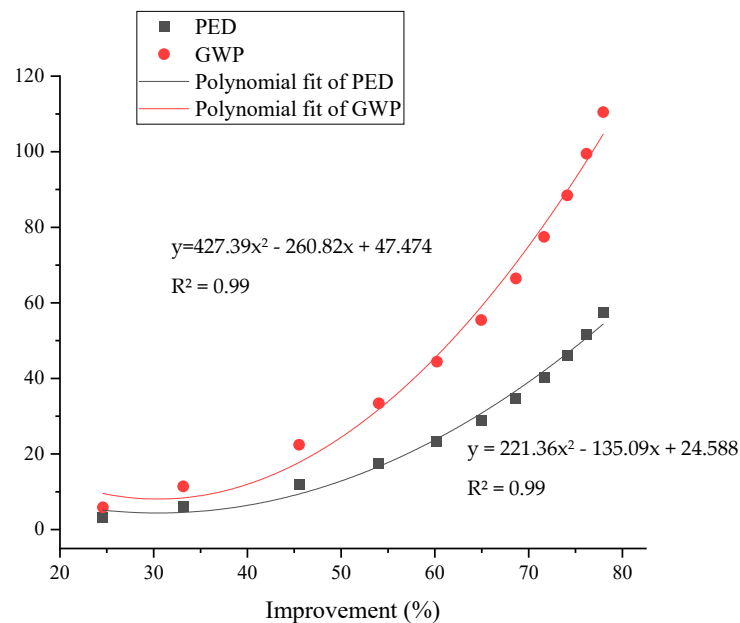


Figure 12. Relationship between thermal performance improvement of an exterior wall and the environmental impact.

As shown in Figure 13, when the thermal performance of a rock wool insulation roof is improved within 40%, the environmental impact indicators change slowly. When the increase is greater than 40%, the change rates of PED and GWP begin to increase.

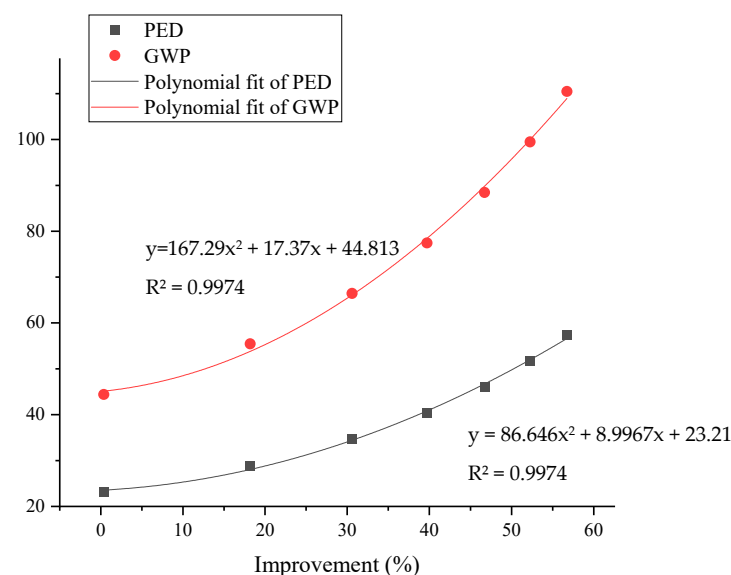


Figure 13. Relationship between thermal performance improvement of a roof and the environmental impact.

3.2.4. Cost Analysis of a Building Envelope

According to the costs of the thermal insulation materials of the envelope in Table 5, the costs of the four thermal insulation layers with different thicknesses were quantified. Quantitative indicators of the costs of different types of windows are summarized in Table 6.

Taking the prototype residential building in a cold area as an example, the costs of a rock wool insulation exterior wall and roof under different thicknesses of insulation layer were analyzed, and the results are shown in Table 20. As the thickness of rock wool increases, the thermal performance of exterior walls and roofs gradually improves, and the costs also increase. Therefore, the relationship between thermal performance improvement and costs was quantitatively analyzed.

Table 20. Thermal performance and costs of a rock wool exterior wall and roof.

Thickness mm	Exterior Wall		Roof		RMB/m ²
	U-Value W/(m ² ·k)	Improvement	U-Value W/(m ² ·k)	Improvement	
10	0.53	24.61%	1.91	N/A	2.86
20	0.47	33.21%	1.30	N/A	5.72
40	0.38	45.61%	0.80	N/A	11.44
60	0.32	54.13%	0.57	N/A	17.16
80	0.28	60.34%	0.45	0.40%	22.88
100	0.24	65.07%	0.37	18.27%	28.6
120	0.22	68.79%	0.31	30.70%	34.32
140	0.20	71.80%	0.27	39.85%	40.04
160	0.18	74.28%	0.24	46.87%	45.76
180	0.17	76.35%	0.21	52.42%	51.48
200	0.15	78.12%	0.19	56.92%	57.2

Figures 14 and 15 show the relationship between the thermal performance improvement and costs of an exterior wall and roof. When the thermal performance of the exterior wall is improved by less than 50%, the economic cost increases slightly, and when it is improved by more than 50%, the initial investment begins to increase rapidly. The increase of roof thermal performance has little effect on the investment cost, which is a trend of slow growth.

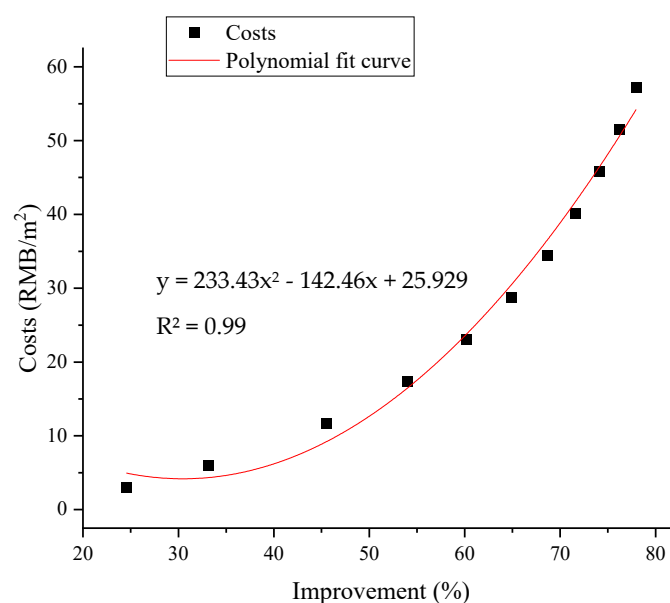


Figure 14. Relationship between thermal performance improvement of an exterior wall and costs.

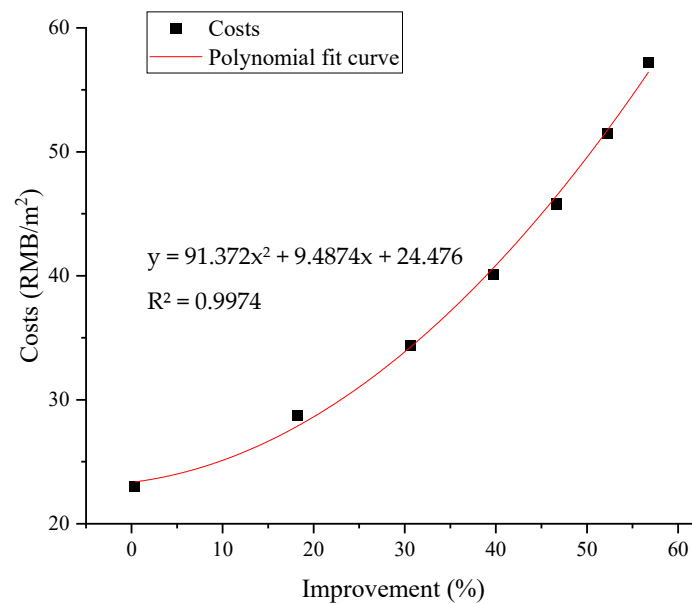


Figure 15. Relationship between thermal performance improvement of a roof and costs.

In this research, we quantitatively analyzed the heat transfer coefficients of exterior walls and roofs with four different thermal insulation materials under different thicknesses. The corresponding thermal performance improvement ranges of different exterior walls and roofs were further analyzed, and a database of common practices was established. Quantitative analysis of the thermal performance of 10 kinds of common windows and the corresponding thermal performance improvement range was performed, leading to the establishment of a common windows database. According to the life cycle environmental impact assessment index, we established a database of the environmental impact load formed by different envelope practices. At the same time, the economic cost database of thermal performance improvement of an envelope was established through investment analysis. Finally, the quantitative data of the aforementioned individual indicators were summarized into a multi-index database of green building envelope practices, as presented in Tables 21–26, for residential and public buildings in cold areas.

Table 21. External wall insulation of residential buildings in a cold area.

Material	Index	Improvement							
		5%	10%	20%	30%	40%	50%	60%	70%
Rock wool	Thickness (mm)	10	10	10	20	40	60	80	140
	PED/m ²	2.86	2.86	2.86	5.72	11.44	17.16	22.88	40.04
	GWP/m ²	5.52	5.52	5.52	11.04	22.09	33.13	44.18	77.31
	RMB/m ²	3.02	3.02	3.02	6.03	12.06	18.10	24.13	42.22
PU	Thickness (mm)	10	10	10	10	20	40	60	80
	PED/m ²	2.36	2.36	2.36	2.36	4.72	9.44	14.15	18.87
	GWP/m ²	4.03	4.03	4.03	4.03	8.05	16.10	24.15	32.20
	RMB/m ²	6.80	6.80	6.80	6.80	13.60	27.20	40.80	54.40
EPS	Thickness (mm)	10	10	10	20	40	60	80	120
	PED/m ²	1.69	1.69	1.69	3.38	6.77	10.15	13.54	20.30
	GWP/m ²	2.42	2.42	2.42	4.84	9.68	14.52	19.36	29.04
	RMB/m ²	3.48	3.48	3.48	6.96	13.92	20.88	27.84	41.76
XPS	Thickness (mm)	10	10	10	20	40	40	60	100
	PED/m ²	2.96	2.96	2.96	5.92	11.84	11.84	17.77	29.61
	GWP/m ²	4.24	4.24	4.24	8.47	16.94	16.94	25.41	42.35
	RMB/m ²	5.01	5.01	5.01	10.02	20.04	20.04	30.06	50.10

Table 22. Roof insulation of residential buildings in a cold area.

Material	Index	Improvement							
		5%	10%	20%	30%	40%	50%	60%	70%
Rock wool	Thickness (mm)	100	100	120	140	160	180	220	300
	PED/m ²	28.60	28.60	34.32	40.04	45.76	51.48	62.92	85.80
	GWP/m ²	55.22	55.22	66.26	77.31	88.35	99.40	121.48	165.66
	RMB/m ²	30.16	30.16	36.19	42.22	48.26	54.29	66.35	90.48
PU	Thickness (mm)	60	60	60	80	100	100	140	180
	PED/m ²	14.15	14.15	14.15	18.87	23.59	23.59	33.03	42.46
	GWP/m ²	24.15	24.15	24.15	32.20	40.25	40.25	56.35	72.45
	RMB/m ²	40.80	40.80	40.80	54.40	68.00	68.00	95.20	122.40
EPS	Thickness (mm)	80	80	100	100	120	140	180	240
	PED/m ²	13.54	13.54	16.92	16.92	20.30	23.69	30.46	40.61
	GWP/m ²	19.36	19.36	24.20	24.20	29.04	33.88	43.56	58.08
	RMB/m ²	27.84	27.84	34.80	34.80	41.76	48.72	62.64	83.52
XPS	Thickness (mm)	80	80	80	100	120	140	160	220
	PED/m ²	23.69	23.69	23.69	29.61	35.53	41.45	47.38	65.14
	GWP/m ²	33.88	33.88	33.88	42.35	50.82	59.29	67.76	93.17
	RMB/m ²	40.08	40.08	40.08	50.10	60.12	70.14	80.16	110.22

Table 23. External window of residential buildings in a cold area.

Improvement	Frame	Glass	PED	GWP	RMB/m ²
5%	PVC	5 + 12Ar + 5	4.51	9.88	359
10%	Heat broke aluminum	5low-e + 6A + 5	6.73	15.25	450
20%	Heat broke aluminum	5low-e + 8A + 5	6.73	15.25	474
30%	Heat broke aluminum	5low-e + 12A + 5	6.73	15.25	568
40%	Heat broke aluminum	5low-e + 13Ar + 5	6.73	15.25	650
50%	PVC	5low-e + 12A + 5 + 12A + 5	5.31	11.7	483
60%	PVC	5low-e + 13Ar + 5 + 13Ar + 5	5.31	11.7	540

Table 24. Roof insulation of public buildings in a cold area.

Material	Index	Improvement							
		5%	10%	20%	30%	40%	50%	60%	70%
Rock wool	Thickness (mm)	40	40	60	80	100	120	180	240
	PED/m ²	11.44	11.44	17.16	22.88	28.60	34.32	51.48	68.64
	GWP/m ²	22.09	22.09	33.13	44.18	55.22	66.26	99.40	132.53
	RMB/m ²	12.06	12.06	18.10	24.13	30.16	36.19	54.29	72.38
PU	Thickness (mm)	20	20	20	40	60	80	100	140
	PED/m ²	4.72	4.72	4.72	9.44	14.15	18.87	23.59	33.03
	GWP/m ²	8.05	8.05	8.05	16.10	24.15	32.20	40.25	56.35
	RMB/m ²	13.60	13.60	13.60	27.20	40.80	54.40	68.00	95.20
EPS	Thickness (mm)	40	40	40	60	80	100	140	200
	PED/m ²	6.77	6.77	6.77	10.15	13.54	16.92	23.69	33.84
	GWP/m ²	9.68	9.68	9.68	14.52	19.36	24.20	33.88	48.40
	RMB/m ²	13.92	13.92	13.92	20.88	27.84	34.80	48.72	69.60
XPS	Thickness (mm)	30	40	40	60	80	100	120	180
	PED/m ²	8.88	11.84	11.84	17.77	23.69	29.61	35.53	53.30
	GWP/m ²	12.71	16.94	16.94	25.41	33.88	42.35	50.82	76.23
	RMB/m ²	15.03	20.04	20.04	30.06	40.08	50.10	60.12	90.18

Table 25. External window of public buildings in a cold area.

Material	Index	Improvement							
		5%	10%	20%	30%	40%	50%	60%	70%
Rock wool	Thickness (mm)	100	120	120	140	160	200	260	330
	PED/m ²	28.60	34.32	34.32	40.04	45.76	57.20	74.36	94.38
	GWP/m ²	55.22	66.26	66.26	77.31	88.35	110.44	143.57	182.23
	RMB/m ²	30.16	36.19	36.19	42.22	48.26	60.32	78.42	99.53
PU	Thickness (mm)	60	60	80	80	100	120	160	200
	PED/m ²	14.15	14.15	18.87	18.87	23.59	28.31	37.74	47.18
	GWP/m ²	24.15	24.15	32.20	32.20	40.25	48.30	64.40	80.50
	RMB/m ²	40.80	40.80	54.40	54.40	68.00	81.60	108.80	136.00
EPS	Thickness (mm)	80	100	100	120	140	160	200	280
	PED/m ²	13.54	16.92	16.92	20.30	23.69	27.07	33.84	47.38
	GWP/m ²	19.36	24.20	24.20	29.04	33.88	38.72	48.40	67.76
	RMB/m ²	27.84	34.80	34.80	41.76	48.72	55.68	69.60	97.44
XPS	Thickness (mm)	80	80	100	100	120	160	180	260
	PED/m ²	23.69	23.69	29.61	29.61	35.53	47.38	53.30	76.99
	GWP/m ²	33.88	33.88	42.35	42.35	50.82	67.76	76.23	110.11
	RMB/m ²	40.08	40.08	50.10	50.10	60.12	80.16	90.18	130.26

Table 26. External window of public buildings in a cold area.

Improvement	Frame	Glass	PED	GWP	RMB/m ²
5%	Heat broke aluminum	5low-e + 12A + 5	6.73	15.25	568
10%	Heat broke aluminum	5low-e + 13Ar + 5	6.73	15.25	650
20%	Heat broke aluminum	5low-e + 13Ar + 5	6.73	15.25	650
30%	PVC	5low-e + 12A + 5 + 12A + 5	5.31	11.7	483
40%	PVC	5low-e + 10Ar + 5 + 8Ar + 5	5.31	11.7	495

3.3. Analysis of Building Heat Consumption

3.3.1. Building Heat Consumption

The standard for the energy consumption of buildings (GB/T 51161-2016) [44] requires the restriction value and guidance value for the heat consumption level of civil buildings. From Table 27 and Figure 16, it is apparent that in the 10 green building projects tested, all of the winter heat consumption values meet the restriction value requirements, and the proportion of projects that meet the guidance value requirements reaches 80%. From these results, it can be concluded that the actual thermal insulation effect of the green building envelope is good, and most of them meet the requirements of the building heat consumption limit.

Table 27. Heat consumption of green buildings in a cold area.

Project	Floor Area m ²	Heat Consumption GJ/a	Heat Consumption Per Unit Area GJ/m ² ·a	Constraint Value GJ/m ² ·a	Bootstrap Value GJ/m ² ·a
1	10,723	1922.3	0.18	0.25	0.2
2	129,928	41,281.9	0.13	0.25	0.2
3	6628.1	1139.6	0.17	0.23	0.15
4	10,762	1838.0	0.17	0.25	0.2
5	14,700	788.9	0.05	0.25	0.2
6	8091	736.5	0.09	0.25	0.2
7	24,648	4616.4	0.19	0.25	0.2
8	20,861	1766.7	0.08	0.21	0.14
9	16,724	1416.4	0.08	0.21	0.14
10	3283.8	599.3	0.18	0.21	0.14

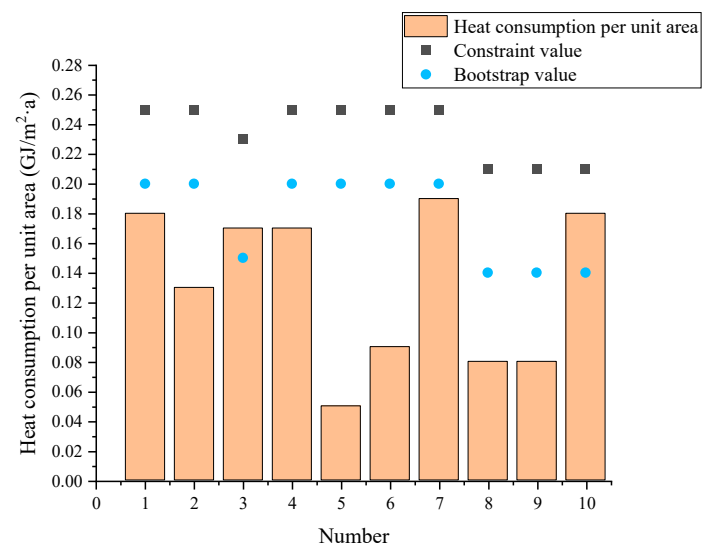


Figure 16. The relationship between heat consumption and the limit value.

In order to analyze the relationship between the actual heat consumption and thermal performance of exterior walls, roofs, and windows, the thermal performance improvement range of each part of the test project envelope was calculated and arranged as shown in Table 28.

Table 28. Improvement of the thermal performance in practical projects.

Project	U-Value of External Wall W/(m ² ·K)			U-Value of Roof W/(m ² ·K)			U-Value of External Window W/(m ² ·K)			Heat Consumption Per Unit Area GJ/m ² ·a
	Design	Limit	Improvement	Design	Limit	Improvement	Design	Limit	Improvement	
1	0.4	0.6	33.33%	0.41	0.55	25.45%	2.2	2.7	18.52%	0.18
2	0.5	0.6	16.67%	0.35	0.55	36.36%	2	2.7	25.93%	0.13
3	0.43	0.6	28.33%	0.39	0.5	22.00%	2.8	2.8	0.00%	0.17
4	0.44	0.6	26.67%	0.15	0.55	72.73%	2.5	2.7	7.41%	0.17
5	0.461	0.6	23.17%	0.418	0.55	24.00%	2	2.3	13.04%	0.05
6	0.18	0.6	70.00%	0.14	0.55	74.55%	1.1	2.4	54.17%	0.09
7	0.51	0.6	15.00%	0.49	0.55	10.91%	2.7	2.7	0.00%	0.19
8	0.34	0.6	43.33%	0.42	0.55	23.64%	2	2.3	13.04%	0.08
9	0.42	0.7	40.00%	0.27	0.45	40.00%	2	2.3	13.04%	0.08
10	0.31	0.63	50.79%	0.49	0.55	10.91%	2.7	2.8	3.57%	0.18

An improvement of the thermal performance of the enclosure structure will reduce the thermal load of the building, but the actual heat consumption of the project might not decrease. As shown in Figure 17, when the thermal performance of the three parts of the building envelope is improved more closely, they consume less heat, such as Item 5 and Item 6. However, when the thermal performance of the roof part is improved significantly and the window part is improved slightly, the heat consumption is still large, such as Item 4. Therefore, it is not comprehensive enough to explore the influencing factors of heat consumption only by analyzing the improvement of the thermal performance. At the same time, the energy consumption limit and actual heat consumption of residential buildings are generally lower than those of public buildings, except for the energy consumption of public building projects 5 and 6, which was found to be lower, and the energy consumption of residential project 10, which was higher. This is because projects 5 and 6 are three-star green buildings which perform better in energy-saving operation and management. Additionally, project 10 has a better thermal performance in terms of the external walls, the performance of the exterior windows is poor, and the non-energy saving behavior of the households also increases the energy consumption [45].

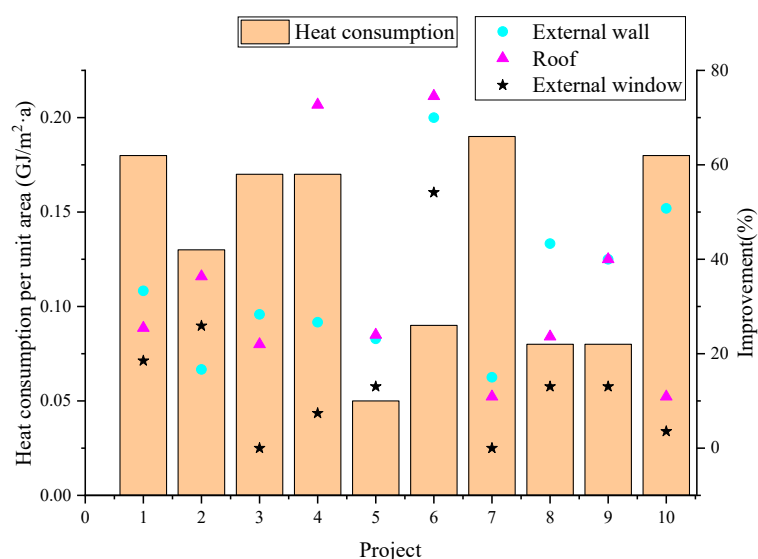


Figure 17. The relationship between thermal performance improvement and heat consumption.

As shown in Figure 18, the comprehensive heat transfer coefficients of the envelope of 10 projects are arranged in descending order. Although the comprehensive heat transfer coefficients are reduced, the actual heat consumption in winter does not show a significant correlation with them. The heat consumption of green buildings in winter is affected by the thermal performance of the envelope structure, as well as other factors, such as the window-wall ratio, performance matching between the building envelope structures, improper operation during the use of the building, and so on. In addition, the comprehensive heat loss coefficient reflects the relationship between actual heat consumption and the thermal performance of the envelope. It can be used as an index to evaluate the thermal insulation performance of the building envelope structure and considers the influence of the U-value and area of the external wall, window, and roof. As shown in Figure 19, the variation trend of the comprehensive heat loss coefficient of the envelope structure is close to that of the comprehensive heat transfer coefficient. Therefore, it can not only characterize the comprehensive thermal performance of the envelope structure, but also be calculated from the actual heat consumption, and can also represent the actual heat consumption of the building.

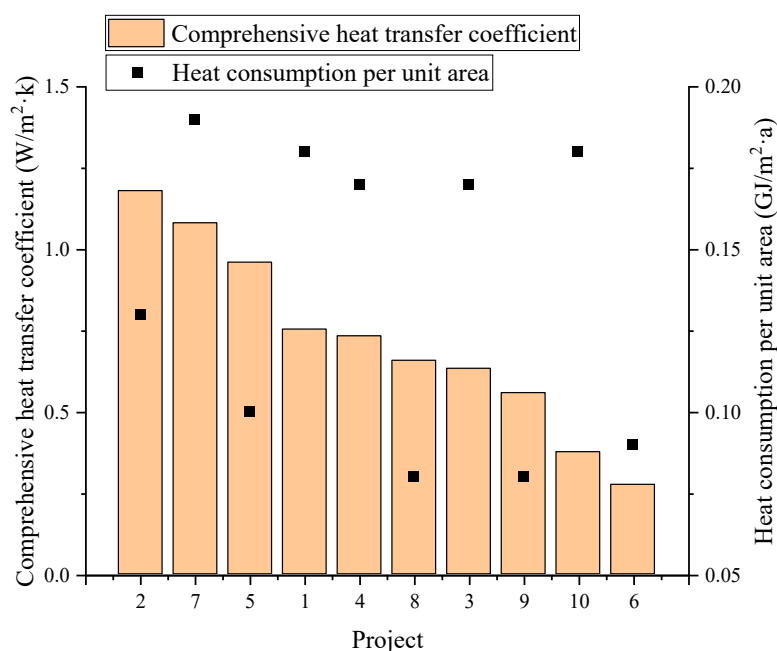


Figure 18. Relationship between the comprehensive heat transfer coefficient and heat consumption.

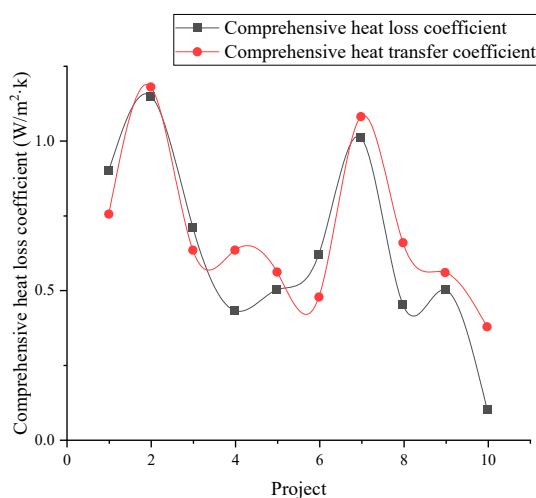


Figure 19. Variation trend of the comprehensive heat loss coefficient and comprehensive heat transfer coefficient.

3.3.2. Sensitivity Analysis of the Comprehensive Heat Loss Coefficient

The building model used for sensitivity analysis refers to Items 1 and 10 tested in this paper, which are typical public and residential buildings in cold areas, respectively. Taking the actual shape coefficient, heat transfer coefficient, window-wall ratio, and indoor human activities as boundary conditions, the Design Builder software was used to establish the model and calculate the winter heat consumption. The basic information of the project and the results of simulated heat consumption are shown in Table 29.

Table 29. Basic information of typical projects.

Type	U-Value W/m²·K			Heat Consumption kWh/a	Envelope Area m²
	External Window	External Wall	Roof		
Public building	2.2	0.4	0.41	522,327.1	7081.5
Residential building	2.7	0.31	0.49	174,024.8	21,084.2

In order to discuss the influence of the thermal performance of the external wall on the comprehensive heat loss coefficient of the envelope, the thermal performance of the external wall only was improved, while the roof and window remained unchanged, and the heat consumption was simulated. We calculated the comprehensive heat loss coefficient according to Equations (7)–(9). Subsequently, we further calculated the sensitivity coefficient IC according to Equation (10) and Figures 20 and 21 show that although the comprehensive heat loss coefficients of public buildings and residential buildings are quite different, the sensitivity coefficients resulting from the change of thermal performance of external walls are not very different; the IC range of public buildings is 0.278–0.347 and that of residential buildings is 0.296–0.381. When the improvement of exterior wall reaches 20%, the change of sensitivity coefficient begins to slow down, and the comprehensive heat loss coefficient tends to be stable. Therefore, there is a linear relationship between the thermal performance of external walls and the comprehensive thermal loss coefficient.

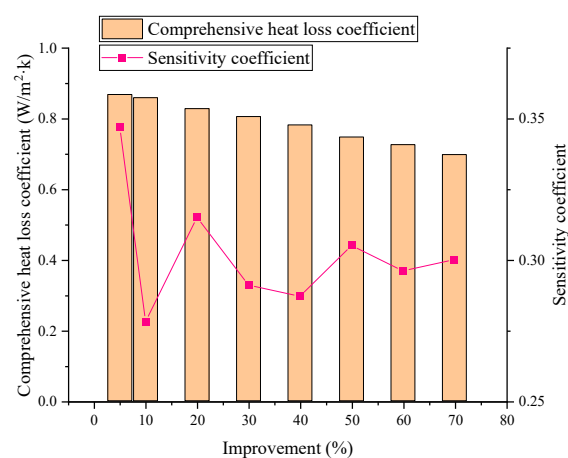


Figure 20. Sensitivity analysis of public building exterior walls.

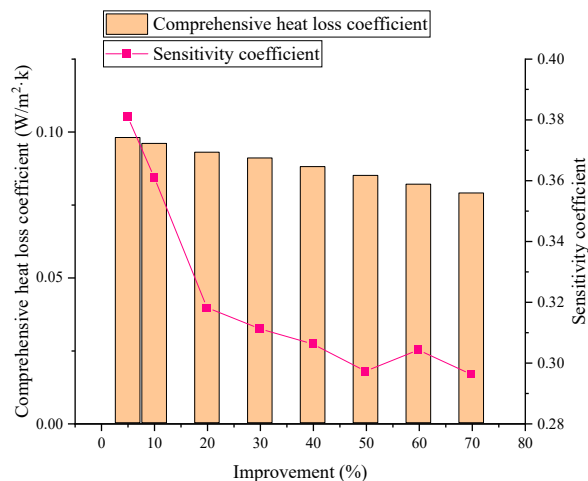


Figure 21. Sensitivity analysis of residential building exterior walls.

Figures 22 and 23 show that the improvement of the roof thermal performance has less influence on the comprehensive heat loss coefficient of the enclosure structure. The IC range of public buildings is 0.15–0.186 and that of residential buildings is 0.062–0.078. Compared to public buildings, the IC fluctuation of residential buildings is less. When the thermal performance of public building roofs increases by 30%, the impact on the comprehensive heat loss coefficient suddenly increases and then begins to stabilize. In residential buildings, the roof thermal performance has little effect and is not the main factor.

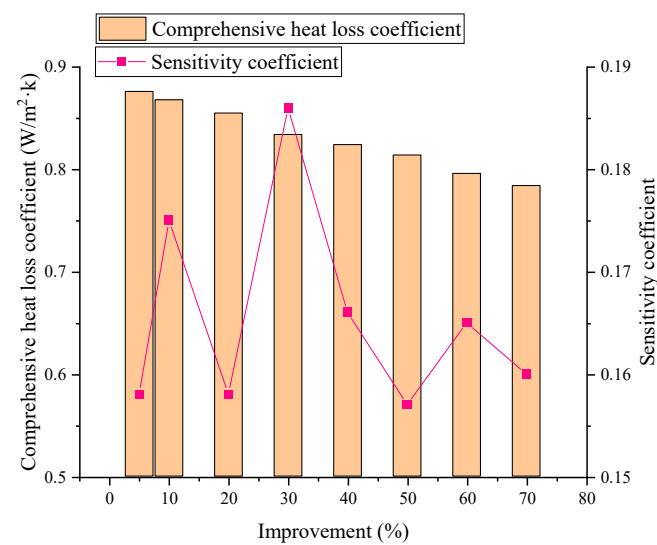


Figure 22. Sensitivity analysis of public building roofs.

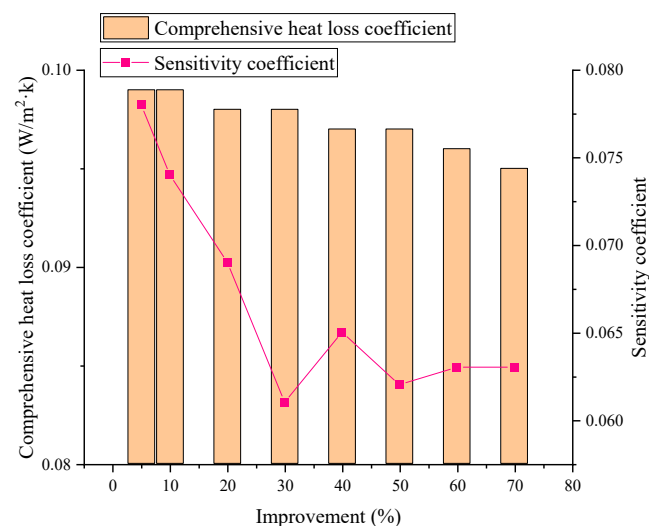


Figure 23. Sensitivity analysis of residential building roofs.

Figures 24 and 25 show that the thermal performance of external windows has a significant influence on the comprehensive heat loss coefficient of the enclosure. The IC of public buildings ranges from 0.119 to 0.305, which is similar to the IC of external walls. The IC of residential buildings ranges from 0.358 to 1.084, which is the most important factor. As is evident from Figure 24, when the thermal performance of the outer window is improved by 30%, the influence on the comprehensive heat loss coefficient of the enclosure structure is the greatest, and the influence becomes less and then tends to be stable. Figure 25 shows that in residential buildings, the influence of the thermal performance of external windows on comprehensive heat loss is at a high level, which begins to decline after increasing by 10% and then tends to stabilize at 0.6. The linear equations of thermal performance improvement and the comprehensive thermal loss coefficient are $y = 0.0227x + 0.9062$ and $R = 0.9762$ (Public building), and $y = 0.0058x + 0.1027$ and $R = 0.9804$ (Residential building).

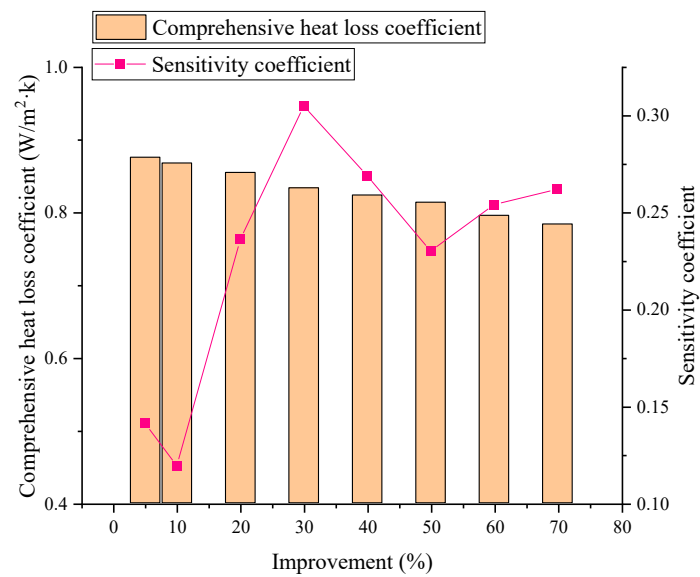


Figure 24. Sensitivity analysis of public building exterior windows.

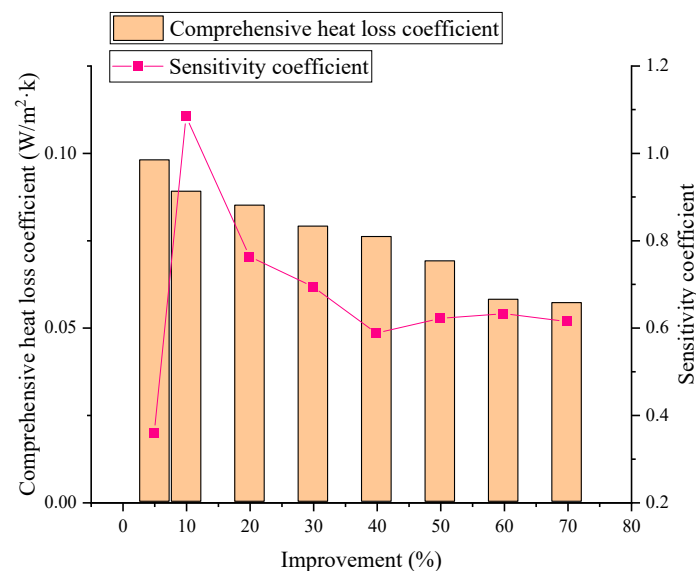


Figure 25. Sensitivity analysis of residential building exterior windows.

3.3.3. Modified Comprehensive Heat Loss Coefficient

From the above analysis, it is apparent that in both public buildings and residential buildings, the influence of exterior walls and windows on building heat consumption is greater and the influence of roofs is relatively lower. Therefore, the comprehensive heat loss coefficient can be determined by the thermal performance of exterior walls and windows and subsequently, improvement of the calculation method can be realized. In this paper, we use the regression analysis method in SPSS software to calculate the linear regression Equation (12), with the comprehensive heat loss coefficient as the dependent variable and the heat transfer coefficient of the exterior wall and window as the independent variable.

$$\hat{k}_z = 0.481 + 3.249U_{wall} - 0.446U_{win}, \quad (12)$$

where \hat{k}_z is the modified comprehensive heat loss coefficient, $W/m^2 \cdot K$; U_{wall} is the heat transfer coefficient of the external wall, $W/m^2 \cdot K$; and U_{win} is the heat transfer coefficient of the external window, $W/m^2 \cdot K$.

According to Equation (12), the comprehensive heat loss coefficient of measured items is calculated to verify the accuracy of the formula. The verification results presented in Table 30 show that except for the maximum error of item 10, the errors of the corrected calculation results of other items are within $\pm 15\%$ and the trend of change is shown in Figure 26. The comprehensive heat loss coefficient is consistent with the trend of change of the corrected results. If the number of samples is increased in future research, the error value of the corrected calculation results will be further reduced. Therefore, Equation (12) can be used to calculate and construct the correct results for the comprehensive heat loss coefficient of the building envelope.

Table 30. Modified calculation results.

Project	$k_z(\text{W/m}^2\cdot\text{K})$	$\hat{k}_z(\text{W/m}^2\cdot\text{K})$	Error
1	0.9	0.80	−11.2%
2	1.15	1.26	9.4%
3	0.71	0.63	−11.4%
4	0.43	0.37	−13.2%
5	0.50	0.56	11.4%
6	0.62	0.58	−7.2%
7	1.01	0.93	−7.5%
8	0.45	0.43	−3.6%
9	0.5	0.43	−13.3%
10	0.1	0.28	184.0%

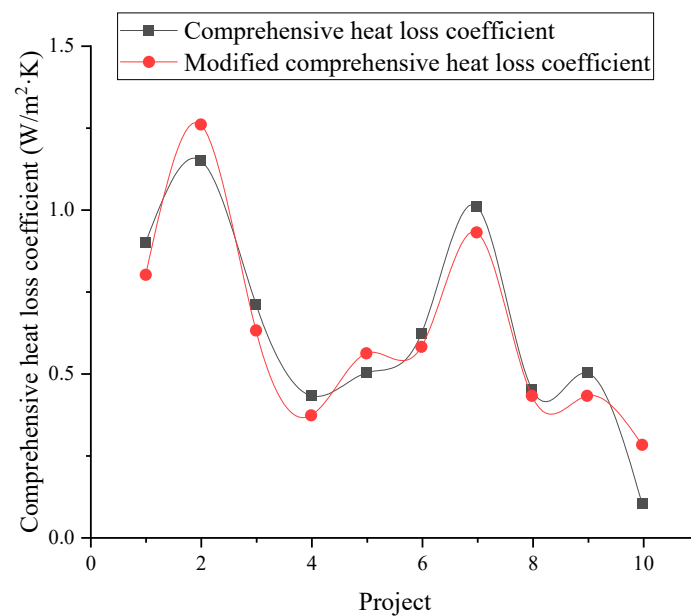


Figure 26. Validation of the comprehensive heat loss coefficient.

4. Results

4.1. Multi-Index Comprehensive Evaluating Model

According to the quantitative results of green building envelope practices in a cold area, we can get the calculation equations (Equations (13)–(17)) of the thermal performance, environmental impact, and economic cost of different practices. Taking the rock wool insulation exterior wall and roof as examples, we can establish the multi-index model.

$$U_{wall} = 10^{-5}x^2 - 0.0042x + 0.5477 \quad (13)$$

$$U_{roof} = 13.067x^{-0.782} \quad (14)$$

$$PED = 0.286x \quad (15)$$

$$GWP = 0.5522x \quad (16)$$

$$COST = 0.3016x, \quad (17)$$

where x is the thickness of insulation material, mm.

First, the index values of rock wool with different thicknesses were calculated according to the aforementioned equations. The thickness range was 10 to 200 mm. Thereafter, MATLAB was used to make the indicators dimensionless, as shown in Tables 31 and 32. Finally, according to the different importance of each index, the weight of each index was determined by the method of quadrant weight assignment, and the comprehensive score under different thicknesses of insulation layer was calculated using Equation (11).

Table 31. Comprehensive score table of a rock wool insulation exterior wall.

Thickness mm	Weight Value of Index				Score Z
	$\overline{k_q}$	\overline{PED}	\overline{GWP}	\overline{COST}	
	0.5	0.125	0.125	0.25	
10	0.00	1	1	1	0.50
20	0.098	0.947	0.947	0.947	0.523
40	0.278	0.842	0.842	0.842	0.560
60	0.439	0.737	0.737	0.737	0.588
80	0.579	0.632	0.632	0.632	0.605
100	0.699	0.526	0.526	0.526	0.613
120	0.800	0.421	0.421	0.421	0.610
140	0.880	0.316	0.316	0.316	0.598
160	0.940	0.211	0.211	0.211	0.575
180	0.980	0.105	0.105	0.105	0.543
200	1	0	0	0	0.50

Table 32. Comprehensive score table of a rock wool insulation roof.

Thickness mm	Weight Value of Index				Score Z
	$\overline{k_q}$	\overline{PED}	\overline{GWP}	\overline{COST}	
	0.5	0.125	0.125	0.25	
10	0	1	1	1	0.500
20	0.354	0.947	0.947	0.947	0.651
40	0.649	0.842	0.842	0.842	0.745
60	0.779	0.737	0.737	0.737	0.758
80	0.852	0.632	0.632	0.632	0.742
100	0.899	0.526	0.526	0.526	0.712
120	0.931	0.421	0.421	0.421	0.676
140	0.955	0.316	0.316	0.316	0.636
160	0.974	0.211	0.211	0.211	0.592
180	0.988	0.105	0.105	0.105	0.547
200	1	0	0	0	0.500

From the above calculation results, the optimum thickness of rock wool for the external wall should be 100 and 60 mm for the roof. For other types of enclosure, the same method can be used for evaluation, which need not be detailed here.

4.2. Model Application

Taking the prototype residential building in a cold area as an example, we used the multi-index evaluation model to evaluate the practice of the envelope and then selected the best building envelope scheme. The analysis and evaluation process is as follows:

(1) According to the simulation results in Table 7 and Figure 5, when the overall thermal performance of the building is improved between 5% and 50%, good results can be achieved, and when it reaches 40%, the improvement effect is the best;

(2) Table 8 and Figure 6 show that in the simulation results of thermal load, the proportion of external windows and external walls is large, about 40–50%, while the proportion of roof heat load is small, about 5%;

(3) Figures 21, 23 and 25 show the sensitivity analysis results of the thermal performance of the building envelope. We can see that the comprehensive heat loss coefficient is more sensitive to the performance improvement of external walls and windows, and improvement of the roof thermal performance has little impact on it;

(4) According to the analysis above, we determined that the thermal performance of the external wall and window can be improved by 40% and that of the roof can be improved by 5%. Subsequently, the corresponding scheme can be seen in Tables 21–26, according to the promotion range, and the comprehensive score can be calculated according to the multi-index evaluation model, as shown in Table 33. The optimal scheme can be selected after comparison: XPS board (30 mm) for external wall insulation, PU board (60 mm) for roof insulation, and a heat broke aluminum frame (5Low-e + 13Ar + 5) for external windows.

Table 33. Multi-index evaluation results of a residential building envelope in a cold area.

Type	Rock Wool	PU	EPS	XPS
Exterior wall	0.56 (40 mm)	0.579 (20 mm)	0.598 (30 mm)	0.604 (30 mm)
Roof	0.712 (100 mm)	0.776 (60 mm)	0.747 (80 mm)	0.750 (80 mm)
Exterior window	Heat broke aluminum frame (5low-e + 13Ar + 5)			

5. Discussion

The heat load simulation results in Figures 5 and 7 show the relationship between the improvement range of the building thermal performance and the heat load. When the thermal performance of a residential building envelope is improved by 5–50%, a better effect can be achieved, and the best improvement range is 40%. When the thermal performance is improved by 29%, it is close to the four-step energy efficiency standard (JGJ 26-2018) [11] implemented on August 1, 2019. When the improvement of the thermal performance reaches 36% and 43%, respectively, it corresponds to the requirements of 10% and 20% improvement of the envelope based on the four-step energy saving standard in the Assessment Standard for Green Building (GB/T 50378-2019) [13]. This shows the rationality of the two new standards. The effective range of improving the thermal performance of the public building envelope is also 5–50%, and the best range of improving performance is 30%. In addition, the heat load proportion range of two types of buildings is exterior window > exterior wall > roof.

According to the research results, the methods of the green building envelope in a cold area can be summarized. Based on the basic practices of exterior walls and roofs, the heat transfer coefficients of four kinds of insulation layers under different thicknesses, the corresponding thermal performance improvement range, and the heat transfer coefficients and thermal performance improvement range of 10 kinds of common exterior windows were quantitatively analyzed. The life cycle environmental impact assessment index was introduced to analyze the environmental impact of different building envelopes. Simultaneously, an investment analysis was conducted, and the cost of thermal performance improvement was quantified. The results show that the life cycle and environmental impact cost

will increase sharply if the thermal performance of the enclosure is improved too much [46]. Finally, the above quantitative results were summarized into a database of green building envelope practices in cold areas (Tables 21–27), which provides data support for a multi-index evaluation of the green building envelope. However, this paper lacks case tests and research on common buildings and other climate areas. In future research, we can increase the number of projects, expand the research area, and expand and update the building envelope database.

The heat consumption test results (Figure 17) of 10 green building projects show that the actual heat consumption of the building is affected by the thermal performance of the envelopes in three positions. Therefore, to reflect the relationship between the heat consumption and thermal performance of the envelope, the concept of the comprehensive heat loss coefficient was upgraded, and the actual heat consumption of the building was equivalent to the heat transferred by the enclosure in the unit area. The sensitivity analysis of the thermal performance of the exterior wall, roof, and window shows that the exterior wall and window had the greatest impact on the thermal performance of the building envelope, while the roof had the least impact [38]. This is consistent with the results of the thermal load simulation analysis. It shows that the key to improving the thermal performance of the building envelope is to improve the performance of the exterior wall and window. Furthermore, the correction formula of the comprehensive heat loss coefficient was proposed, and the verification results of the comprehensive heat loss coefficient of the measured items were used. Except for the maximum error of project 10, the error of other projects was within $\pm 15\%$. The change trend of the measured value and the corrected value was consistent, so the correction formula Equation (12) is valid.

According to the quantitative database of each index of the building envelope, the multi-index evaluation model and design selection system of the building envelope was established. Through the above analysis and research, the selection principle of the building envelope scheme was determined. According to the evaluation results of the comprehensive score calculation using the database and the multi-index evaluation model, the best envelope scheme for green residential buildings in cold areas is as follows: XPS board (30 mm) for external wall insulation, PU board (60 mm) for roof insulation, and a heat broke aluminum frame (5Low-e + 13Ar + 5) for external windows. The database of building envelope practice needs to be further expanded and updated. The weight coefficient and evaluation index used in the evaluation model can also be adjusted according to the emphasis of different evaluation objectives in practical applications.

6. Conclusions

This paper presents a multi-index evaluation and decision-making method for the green building envelope and applies it to the envelope design of typical residential buildings in the cold areas of northern China. The method of selecting exterior windows, exterior walls, and roofs is discussed in terms of the thermal performance, life cycle cost, and environmental load. This evaluation system includes a multi-index evaluation model and building envelope practice database, which can guide the formulation of relevant design or evaluation standards and can also guide the architectural design or building retrofit works. In future research, through the establishment and analysis of a database of specific application scenarios, this method can also be applied to the evaluation of different types of building envelope in other climatic regions. Moreover, the database of envelope practices also needs to be expanded and updated. In addition, the weight of each index of the multi-index evaluation model needs further study as the change of weight can affect the evaluation results. The selection of weight and index can also be adjusted according to the emphasis of the evaluation purpose. Therefore, the framework proposed in this study has wide application prospects.

On the basis of the energy efficiency standard limit, improving the overall building envelope performance can yield better results. However, when the level of thermal performance improvement is too high, the energy effect is not significant because the proportion of heat consumption of the envelope will be reduced. At the same time, with the increase in thermal performance, the corresponding life

cycle cost and environmental impact will increase significantly. Therefore, it is not wise to over pursue the high level of thermal performance improvement, which should be moderate.

The actual heat consumption of the building is often different from the theoretical calculation results, and the heat transfer coefficient of the envelope cannot directly reflect the actual energy consumption level of the building. In terms of the thermal performance of the enclosure structure, different performance improvement schemes have different effects. The thermal performance improvement of the exterior wall and the exterior window should be balanced as the performance of the roof has little influence on the overall heat consumption of the building. The relationship among the three needs further study. The energy consumption of public buildings is generally higher than that of residential buildings, and the proportion of heat consumption of their external windows is higher. In addition to the influence of the heat transfer coefficient of the enclosure, the building shape coefficient, window-wall ratio [47], orientation, operation mode [48], and other factors will impact the actual heat consumption. In this paper, the prediction model of green building heat consumption in the cold area was established by optimizing the comprehensive heat loss coefficient of the enclosure. In future research, more case studies should be included to improve the accuracy of the prediction model.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A



models.zip

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