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# Cost-Optimal Renovation Solutions for Detached Rural Houses in Severe Cold Regions of China

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**Abstract:** High heating expenses are observed in numerous Chinese rural houses located in severe cold regions due to the high heating demand, inferior envelope performance and low-efficiency heating equipment. The local traditional heating methods include Chinese Kangs and coal boilers with water-based radiators. The intermittent operation and manual regulation of these systems result in significant temperature differences and inadequate thermal comfort. This study presents the cost-optimal envelope renovation solutions with the minimized lifecycle cost (LCC) during a 20-year discount period and $CO_2$ emissions of annual delivered energy consumptions. A single-family detached rural house in Harbin was used as a case building, illustrating the typical state of comparable houses in this climate context. Simulation-based multi-optimization analysis was conducted in this study using the building simulation tool IDA ICE and its integrated optimization tool AutoMOO. The results indicate that the cost-optimal renovation solutions with intermittent and continuous heating can cut $CO_2$ emissions by 30% and 40%, respectively. The LCC with intermittent heating is still 7% greater than its pre-renovation case, which may require external financial support to encourage the renovation conduction, while the LCC with continuous heating decreased by 8% after renovation. According to the comparison results, cost-optimal solutions have significant advantages in both reductions of LCC and $CO_2$ emissions over standard-based solutions. Moreover, utilizing intermittent heating is more effective than continuous heating in demonstrating the positive impacts of envelope renovation on increasing average temperature, decreasing temperature differences and lowering occupied time at low thermal comfort levels.

**Keywords:** optimal renovation solutions; intermittent heating; rural house; lifecycle cost; $CO_2$ emissions; cold climate

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## 1. Introduction

China's 2060 carbon neutrality goal will necessitate a decrease in carbon emissions across all societal sectors. The building sector is one of China's major energy users and carbon emitters. Many efforts have been undertaken by policymakers, architects and engineers to reduce building energy usage and carbon emissions. The current focus remains primarily on public and commercial buildings as well as urban residential buildings. In 2020, the rural residential area in China reached 22.7 billion $m^2$, accounting for 34% of the total floorspace. These rural houses consume 22% of the overall energy consumption of buildings in China [1]. The energy-saving potential of rural residential buildings is also noteworthy.

Rural houses in severe cold regions of northern China are faced with more significant issues than rural houses in warmer areas. The severe cold region is defined as having an average temperature of less than −10 °C during the coldest month and more than

145 days with a daily average temperature of less than 5 °C [2]. Rural houses in this region are mainly constructed by local builders with few restrictions from building codes. The survey results indicate that only 28% of them have thermal insulation installed on external walls, and 2% of houses consider ground floor insulation [3]. Because of the poor envelope performance combined with the extremely low temperature in winter, these houses have a considerable level of heating demand.

Without access to district heating, the primary heating systems in these rural houses are Chinese Kangs (heated beds as living and sleeping platforms) and boilers with water-based radiators, representing 99% and 51% of heating choices, respectively [3]. These traditional heating systems consume coal or biomass and have an efficiency of 30–50% [4,5]. The systems are manually operated intermittently due to economic reasons and traditional customs. Field measurements revealed that this intermittent heating mode might result in a significant daily temperature variation of 8 °C, thus increasing the potential health risk of elderly occupants [6].

Given the large stock of existing rural houses, energy-efficient renovation is more cost-effective and environmentally beneficial than rebuilding [7,8]. Envelope renovation is one solution to lower energy use and improves indoor climate. Several recent studies have worked on this topic to explore the most appropriate renovation plans for existing rural houses located in cold climate conditions. Cui et al.'s research [9] reflected a typical design process of an actual envelope renovation project. The goal of the renovation was to make each envelope component meet the design standard's requirements of newly built rural houses, where their target heat transmittance values were directly assigned. The energy-saving potential and indoor temperature improvement of each retrofit scheme were calculated separately to obtain suggestions for the prioritization of retrofits under limited funds. Li et al.'s renovation project [10] considered adding external wall insulation and applying a novel solar water heating system. A formula was proposed to calculate the optimal insulation thickness of the external walls, which simultaneously weighed the relationship between heating and cooling load and investment and operational cost. Hu et al.'s renovation project [11] considered adding wall insulation and rooftop solar PV systems to a rural house. The passive renovation package included 17 types of wall structures and their various insulation thickness ranges. The optimization goals were maximum energy savings, minimum investment cost and shortest payback periods. Under the premise of meeting the annual energy balance, one cost-optimal plan was selected from each wall type. These 17 cost-optimal solutions were then compared comprehensively, and one final solution was finally determined with the minimum payback period and investment cost, as well as significant energy savings.

Cao et al. [12] viewed investment cost, energy savings and thermal comfort as the optimization objectives of an envelope renovation project. Three objectives were assigned with different entropy weights to figure out the ultimate renovation strategy. Among them, investment cost was given the biggest weight, followed by the adaptive thermal discomfort degree-hours and the energy-saving rate. Shao et al. [13] utilized an orthogonal experimental design to reduce the simulation numbers when finding the optimal renovation solution. It was proposed that when considering 10 variables, only 64 plans in an orthogonal table should be simulated instead of simulating the previous 410 times. Minimizing energy consumption was taken as the goal of optimization. The relationship between each variable and energy consumption was also quantitatively studied to illustrate the effectiveness of different renovation measures on energy consumption reduction. Economic analysis was only used to check the feasibility of the chosen optimal solution.

There are very few studies using optimization algorithms to obtain the optimal renovation solutions for rural detached houses located in Chinese cold regions. Yao et al.'s renovation project [14] considered different shapes, sizes and constructions for the transparent envelope. SPEA-II algorithm was applied to achieve the optimization calculation. Daylighting, energy efficiency and thermal comfort were assigned as optimization objectives. The results revealed that the optimal model could improve the useful daylight

illuminances by 6%, while also cutting the heating and cooling loads by 23% and reducing the predicted percentage of dissatisfied by 12%. However, the study focused on energy saving and indoor comfort. It did not link any economic analysis or environmental impact to the evaluation methods of renovation projects.

Continuous heating systems are often used in cold climates to ensure that the indoor temperature meets high-level thermal requirements, as in northern Europe. Urban residential buildings in Chinese cold regions realize continuous heating through district heating. Rural areas, however, are mostly not covered by heating networks. Due to income constraints and rooted habits, rural residents still operate the heating system intermittently despite the significant indoor temperature fluctuations. However, under this circumstance, they still have a demand for a better thermal comfort environment, which has been proved by Shao and Jin's research [15]. It is illustrated that the tested operative temperatures inside the rural houses were lower than their neutral temperature, around 2 °C in three typical cities in severe cold regions. Several studies have compared intermittent and continuous heating modes applied in rural houses. Ma et al. [16] operated the low-temperature air-to-air heat pumps in rural houses with three different occupant control behaviors, which were continuous, intermittent and irregular operation. The outcomes illustrated that the indoor temperature varied from 10 °C to 23.5 °C under different operation modes, with correspondingly large differences in energy consumption. Liu et al. [17] compared two different operating modes of a solar water heating system, which are "continuous and whole space heating mode" and "time and spatial partition heating mode". An optimal opening time schedule was observed with increased solar fraction, reduced auxiliary heating consumption as well as reduced annual operation costs. However, to the authors' best knowledge, no study has linked different heating modes with the effectiveness of envelope renovation of rural houses located in cold climate conditions in China. That is to say, there is no discussion about how intermittent and continuous heating modes would affect envelope renovation results.

The aforementioned studies clearly indicate the following research gap: few studies have used multi-objective optimization algorithms to find optimal envelope renovation solutions for rural houses in China's severe cold climate context. The optimization objectives are mainly focused on minimizing energy savings and investment costs. No study has addressed $CO_2$ emissions, lifecycle cost perspective or thermal comfort improvement simultaneously for the envelope renovation in this rural context and climate condition. Moreover, the current renovation studies are still confined to the original intermittent heating mode when simulating the performance improvement potential of rural houses, instead of taking into account the scenario of operating continuous heating mode, similar to urban residential buildings. In other words, the studies are vacant in exploring the influence of different heating modes on the envelope renovation potential and the feasibility of shifting to continuous heating in rural houses.

The novelty of this study is that multi-objective optimization algorithms were applied to explore cost-optimal envelope renovation solutions for different lifecycle cost and $CO_2$ emission levels for Chinese rural houses located in severe cold regions, which was not done in any of the previous studies. The indoor climate was also analyzed before and after the renovation. The novelty also comes from comparing the effectiveness of envelope renovation under two different heating modes, traditional intermittent heating and possible continuous heating.

The main objective of this study is to figure out the cost-optimal envelope renovation solutions with Simulation-Based Multi-Optimization (SBMO) analysis in the Chinese rural context and severe cold climate conditions. An important target is also to distinguish between intermittent and continuous heating modes in rural houses both before and after envelope renovation. Indoor climate improvement, economic feasibility and environmental benefits are taken into consideration for evaluating different heating modes and analyzing the viability of switching to continuous heating mode.

## 2. Methods

### *2.1. Research Structure*

The whole research structure of this study includes five major processes, which are modeling, design, optimization, analysis and comparison, as well as results. As shown in Figure 1, the case building was first chosen, and then its model was established and verified based on various data sources. The renovation measures and variables were chosen after comparing the case building's energy performance with current standard requirements. Multi-objective optimization was run separately with intermittent and continuous heating modes to obtain the optimized solutions considering both economic and environmental impacts. For each heating mode, typical optimized solutions on the Pareto-front were chosen and compared with the standard-based renovation solutions. The post-renovation cases were finally compared with pre-renovation cases to analyze the impact of different heating modes and the effectiveness of envelope renovation. The four major processes are explained in more detail in the following sections. Indoor climate, thermal comfort and economic and environmental impacts are also listed as results in Figure 1.

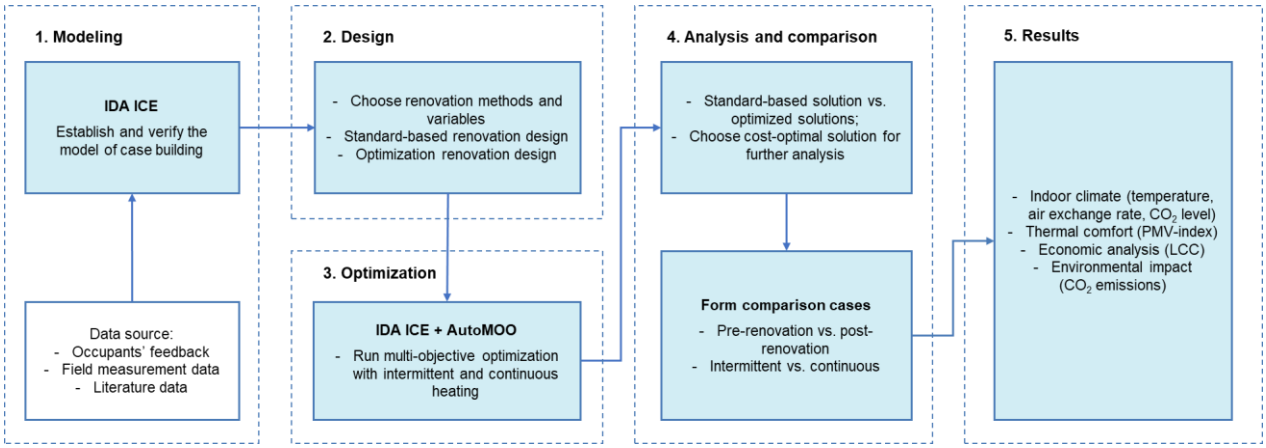



**Figure 1.** General progress scheme in analysis.

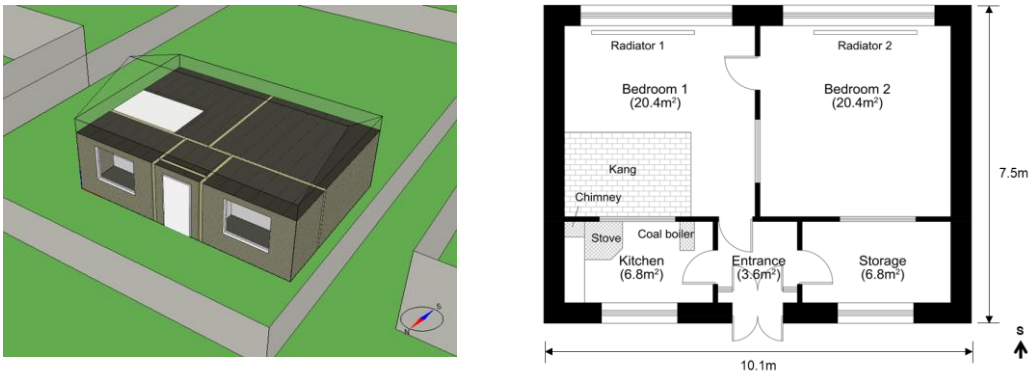
### *2.2. Modeling of Case Building*

#### 2.2.1. Main Features and Structures

This study focuses on the energy performance and renovation potential of the typical rural houses built in Chinese severe cold regions. A single-story detached house located in the rural area of Harbin was selected as a case building in this study, because its construction and local weather conditions could represent a major share of rural houses in this climate region in China. The house is surrounded by similar buildings in a village. The external shading caused by neighboring houses and a fence was taken into account in the simulations (see Figure 2).

The case building contains two bedrooms, one kitchen and one storage room. The main geometry and the floor layout of the case building are presented in Figure 2. Most of the load-bearing structures are brick, which is the dominant structure type in this region. Its envelope structures are presented in Table 1. Its material selections and construction details could represent the common construction approaches in this climate region. It was constructed in the 1990s by local builders. There was no restriction of any energy-efficient building codes in rural areas during that time regarding airtightness or envelope materials. The airtightness of the whole building was set as 7 ACH at 50 Pa according to the average measurement results of this area's rural houses [18]. There is no renovation standard for rural houses in China yet. The envelope performance before the renovation was compared with the current requirements from the national standard for newly built rural houses in Table 1 [19]. It is concluded that the thermal insulation level of the roof meets the requirements. However, the thermal transmittance of external walls, external

windows and entrance door are high, which means a considerable potential for further energy performance improvement.




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

**Figure 2.** (**a**) Main geometry and (**b**) floor layout of the case building.

**Table 1.** Construction details and thermal transmittance of original envelope and the current requirements from the standard for newly built rural houses.

| Envelope | Construction Details (From Inside to Outside) | Original Thermal Transmittance ($W/m^2K$) | Requirements on Thermal Transmittance ($W/m^2K$) |
|---|---|---|---|
| External wall | Mortar 30 mm, brick 490 mm, mortar 30 mm | 0.92 | 0.50 |
| Ground floor | Wood (bedrooms), brick (other rooms), concrete slab 55 mm | 3.15 (bedrooms); 3.88 (other rooms) | No requirement |
| External windows | Two wooden-framed single-glazing windows | 2.30 | 2.20 (southern); 2.00 (other orientations) |
| Entrance door | Wooden door with metal covering | 2.50 | 2.00 |
| Roof | Gypsum 26 mm, perlite insulation 100 mm, wooden board 2 mm, steel roof truss, waterproof sheet, tiles | 0.42 | 0.45 |

#### 2.2.2. HVAC Systems

Only two bedrooms in the case building are heated during winter, while the kitchen is warmed via heat losses from the stove and boiler. It is a common phenomenon in this region due to economic reasons. Without the district heating network cover, the space heating is conducted through two sources: one Chinese Kang system and one coal boiler with two water-based radiators. Raw coal is used as heating fuel.

The traditional Chinese Kang system consists of a stove, a Kang body and a chimney. The stove in the kitchen serves as the heat source and cooking function. The Kang body in bedroom 1 is a cavity constructed of brick, and it leans on the wall between bedroom 1 and the kitchen. The high-temperature smoke flows from the stove, through the hole on the shared wall, into the chamber of Kang, and finally exhausts through the chimney. In winter, people sit on the Kang during the daytime and sleep on it at night. Therefore, the Kang is regarded as a heated bed, serving as a living and sleeping platform. The input power of the stove and Kang were set as 3 kW and 11 kW [20,21]. The Kang and stove are heated three times a day, related to the daily dining time. The Kang's output power reaches its peak in an hour and then decreases within the following four hours [22]. The dining times and weather conditions have an impact on the peak output power of Kang systems because the stove, which is manually controlled, serves as the heat source for both cooking and Kang heating [20]. Generally, the peak output power is more significant during dinner time and with lower outdoor temperatures. The coal boiler is another heat source in the rural house, which is in the kitchen. The water heated by the boiler flows through the pipes

and is then transferred to the radiators in two bedrooms. The water radiator temperatures are 80/60 °C. The peak heating power of the boiler was set as 7.5 kW, with total heating efficiency of 40% [23]. The operating schedule of heating systems in the case building is presented in Table 2. The heating setpoint of 14 °C was used, which was derived from the required heating temperature of the Chinese design standard for newly built rural houses in severe cold regions [19].

**Table 2.** Intermittent heating schedule.

| Parameters | | Values |
|---|---|---|
| Heating season (day) | | 183 (from October 20 to April 20) |
| Heat transfer media | Coal Kang system | Air |
| | Coal boiler | Water |
| Heating schedule | Coal Kang system | 06:00–16:00, 17:00–22:00 |
| | Coal boiler | 07:30–11:00, 13:00–14:30, 17:00–18:00 |

The ventilation is realized by occupants' manually opening windows and doors, as well as the envelope infiltration. The opening profile was summarized according to occupants' feedback and indoor temperature monitoring data. The entrance door was assumed to be always closed. The doors of bedroom 1 and the kitchen are open when the occupant goes for cooking. The door between two bedrooms is open during occupants' non-sleeping time (06:00–22:00). The occupants' feedback indicates that they open the windows in accordance with their comfort sense. Thus, an opening control macro was established to simulate the occupants' opening behavior. Three parameters were selected to determine the window opening conditions, namely outdoor temperature, indoor temperature and indoor $CO_2$ level. The windows would be open when one of the following conditions are fulfilled: (1) the room is occupied, the indoor temperature is higher than 24 °C and the outdoor temperature is between −5 °C and 25 °C; or (2) the room is occupied, and the $CO_2$ level is higher than 1600 ppm during the non-heating season. The constraints of indoor temperature and $CO_2$ level were used to predict occupants' perception of thermal comfort and air quality, while the constraint of outdoor temperature was set to avoid increased heating demand during cold periods.

According to the field survey, there is no additional mechanical cooling system or domestic hot water system in rural houses in this village. Domestic hot water is heated by solar in summer and by public bathing centers in winter. Therefore, domestic hot water consumption was not taken into account in the study.

#### 2.2.3. Internal Gains

There are two adult occupants in the case building. To adapt to the habit of entering and leaving the house frequently for short periods, occupants are accustomed to wearing thick clothing indoors in winter. According to the calculation in Jia et al.'s research [24], the clothing level was assumed to be 1.01 ± 0.41 clo. The power of household appliances and lighting were assumed to be 3.8 $W/m^2$ and 5 $W/m^2$, respectively. These values and profiles were derived from the recommended setting in the Chinese design standard [25].

#### 2.2.4. Weather Data

The case building is situated in the rural area of Harbin with a severe cold climate condition. The heating season in this area lasts 183 days, from October 20 to April 20 of the following year. The IWEC 2 (International Weather for Energy Calculations Version 2) of Harbin, a typical hourly weather file, was chosen to describe the local weather conditions, including the outdoor temperature, relative humidity, wind direction and speed, as well as solar irradiance [26]. The local average temperature is −7 °C during the whole heating

season. Figure 3 shows the annual hourly outdoor temperature in Harbin, with lowest and highest temperatures of −30.5 °C and 34.5 °C, respectively.

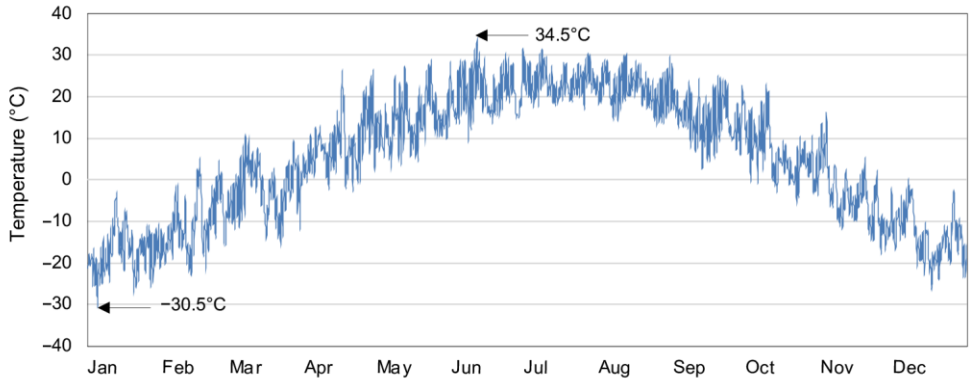



**Figure 3.** Outdoor temperature of Harbin from IWEC 2 weather file.

### *2.3. Design and Optimization*

#### 2.3.1. Simulation and Optimization Methods

IDA Indoor Climate and Energy simulation software (IDA ICE) 5.0 was applied to create and simulate the case building. It is a dynamic simulation tool, which can accurately model the building systems and provides outputs of building energy consumption and indoor climate. This tool has been validated under the standards EN 15255-2007 and EN 15265-2007 [27]. Therefore, IDA ICE was chosen for the modeling and simulation in this study.

The Kang system was modeled in IDA ICE with the modeling principles from Cao et al.'s research [20]. The Kang body was defined as a separate zone. The heat transfer properties and thermal mass of the Kang body itself, as well as the hot air flow path from the kitchen's leakage to the chimney's emission, were all taken into account in detail. In addition, the infiltration and inter-zonal airflows were simulated in detail, taking the wind and temperature differences into account [28].

The automatic optimization tool AutoMOO, which is integrated with IDA ICE 5.0, was used to conduct the multi-objective optimization in this study. Firstly, AutoMOO ran every embedded optimization algorithm for each case, including, for example, genetic algorithms, evolutionary algorithms and gradient-based algorithms. It assessed the performance of each algorithm and decided which algorithms performed better in this optimization case and then chose it to continue finding optimum points. This process came to an end when the predetermined number of simulations was completed.

#### 2.3.2. Thermal Comfort

The predicted mean vote (PMV) index, derived from Fanger's PMV methodology [29], was used to present the thermal comfort results in this study. This methodology developed an equation that quantitatively calculated both environmental and personal factors and led to a score between −3 (cold) and 3 (hot) describing people's thermal sensations.

The categories of PMV level were defined in EN 16798-1:2019 standard [30]. Cut-off points of ±0.2, ±0.5 and ±0.7 were chosen to divide the PMV index into four categories (I–IV). The time spent in a particular PMV category is analyzed as a percentage of the total occupied hours in Section 3.2.2.

#### 2.3.3. Renovation Measures

As mentioned in Section 2.2.1, the energy performance of external walls, windows and entrance door is lower than the standard requirements for newly built rural houses. In addition, there is no thermal insulation on the ground floor, so the heat loss from the ground floor should also be considered. Therefore, external walls, ground floor, external windows and entrance door were chosen as the renovation objects.

Table 3 lists the ranges and types of decision variables of each renovation measure.

**Table 3.** Decision variables of renovation measures used in SBMO analysis.

| | Minimum Value | Maximum Value | Type of Variable |
|---|---|---|---|
| Additional expanded polystyrene (EPS) insulation thickness of external southern walls (mm) | 0 | 200 | Continuous |
| Additional EPS insulation thickness of other external walls (mm) | 0 | 200 | Continuous |
| Additional Extruded polystyrene (XPS) insulation thickness of ground floor (mm) | 0 | 200 | Continuous |
| Renovation of external windows<br>– Original windows, with thermal transmittance of 2.30 W/m$^2$K and total solar heat transmittance (g-value) of 0.76.<br>– Option 1. Installation of two new double-glazing windows, with thermal transmittance of 1.48 W/m$^2$K and g-value of 0.55.<br>– Option 2. Demolition of original outer window-pane and installation of one new double-glazing window-pane, with thermal transmittance of 2.00 W/m$^2$K and g-value of 0.70.<br>– Option 3. Installation of one new triple-glazing windows, with thermal transmittance of 2.10 W/m$^2$K and g-value of 0.62. | Original | New, 1.48 W/m$^2$K | Discrete, 4 options |

The renovation measures for external walls and ground floor were considered as adding new expanded polystyrene (EPS) insulation and extruded polystyrene (XPS) insulation, which are common local affordable materials. The EPS board was added to the outer surface of the original external wall, as well as 10 mm leveling mortar, double-layer glass fiber mesh and 6 mm mortar. The XPS board was added onto the original concrete slab, with 40 mm fine aggregate concrete as the new floor covering. The thermal transmittance of the external walls and floor after renovation depended on the thickness of the insulation materials.

The windows could remain or be replaced with new windows. The window options are presented in detail in Table 3. The entrance door was replaced by an insulated metal door with thermal transmittance of 1.50 W/m$^2$K.

#### 2.3.4. Simulation-Based Multi-Objective (SBMO) Analysis

SBMO analysis was then utilized to obtain the optimal solutions for the envelope renovation. The main process can be seen in Figure 4. The SBMO analysis was carried out by using a computer with 32 CPUs, and a population size of 64 was selected based on the suggestion from the AutoMOO developer. After balancing between computational time and accuracy, 1024 simulation was determined in this study to obtain the optimal solutions. The optimization process kept finding new value combinations to minimize the objectives, and it stopped when the pre-set total simulations were accomplished.

Two conflicting objectives were selected: net present value of lifecycle cost (NPV of LCC) over a 20-year discount period and $CO_2$ emissions of annual delivered energy consumption. The results were presented as NPV of LCC and $CO_2$ emissions per floor area, where the used floor area is total net floor area of the case building (58 m$^2$). The optimization goal was to identify the optimal possible solutions while simultaneously minimizing both financial costs and environmental impacts.

The calculation method of NPV of LCC is as follows:

$$NPV_{LCC,\,20a} = \sum I_{tot} + \sum MR_{tot} + \sum E_{tot} - \sum Res_{tot} \quad (1)$$

$$\sum E_{tot} = \frac{1-(1+r_e)^{-n}}{r_e} \times E_a \quad (2)$$

where $NPV_{LCC,\,20a}$ is the net present value of LCC with a 20-year life-span, CNY; $\sum I_{tot}$ is the overall investment cost for the envelope renovation, accounting for the material cost and the labor cost incurred during demolition and installation (see Table 4), CNY; $\sum MR_{tot}$ is the total maintenance and renewal cost, CNY; $\sum E_{tot}$ is the total energy cost, CNY; $\sum Res_{tot}$ is the total residual value of the energy renovation measures, CNY. $E_a$ is the annual energy cost, CNY/a; $r_e$ is the escalated real interest rate, %/a; $n$ is the discount period of LCC analysis.

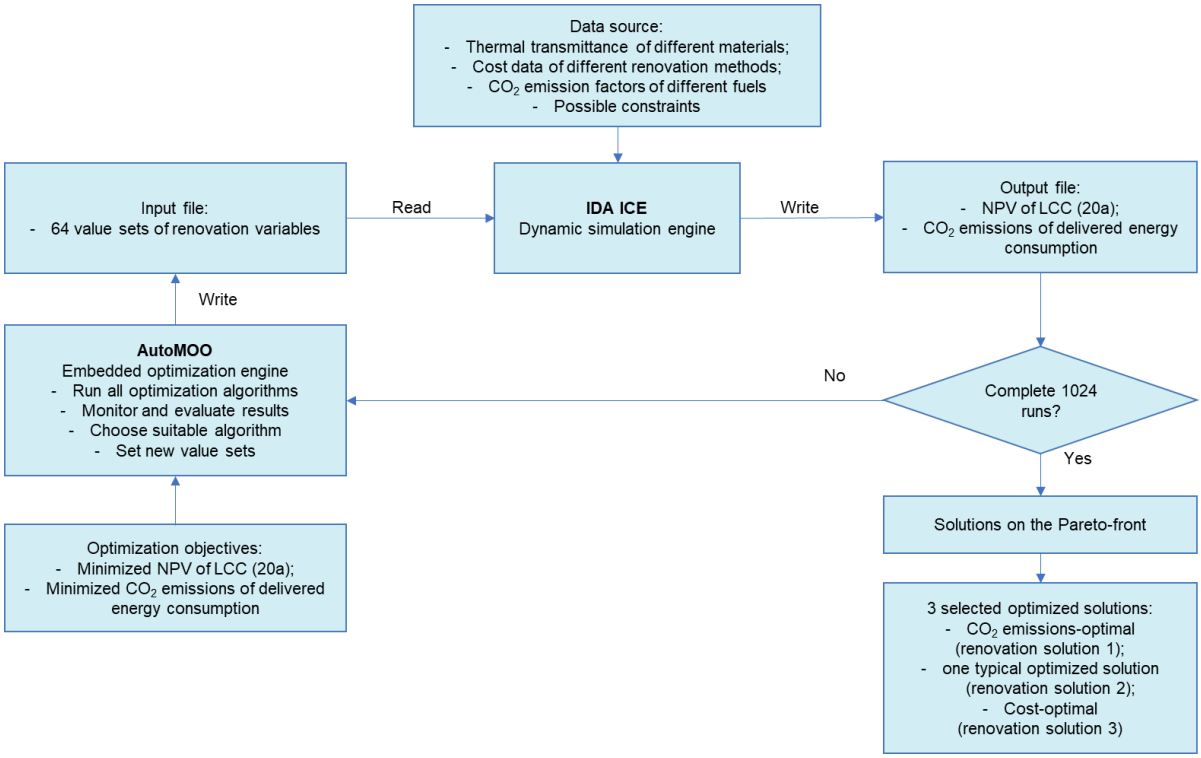



**Figure 4.** Main processes of SBMO with IDA ICE and AutoMOO in this study.

**Table 4.** Cost data of envelope renovation measures.

| Envelope Components | Material Name | Material Cost | Demolition and Installation Cost |
|---|---|---|---|
| External wall | EPS insulation board | 360.0 CNY/insulation-$m^3$ * | 15.4 CNY/wall-$m^2$ |
| | Other materials | 27.3 CNY/wall-$m^2$ | 26.8 CNY/wall-$m^2$ |
| Ground floor | XPS insulation board | 480.0 CNY/insulation-$m^3$ | 11.4 CNY/wall-$m^2$ |
| | Other materials | 18.0 CNY/wall-$m^2$ | 12.0 CNY/wall-$m^2$ |
| External window | Option 1. | 540.0 CNY/window-$m^2$ | 33.8 CNY/window-$m^2$ |
| | Option 2. | 270.0 CNY/window-$m^2$ | 16.9 CNY/window-$m^2$ |
| | Option 3. | 400.0 CNY/window-$m^2$ | 20.7 CNY/window-$m^2$ |
| External door | Insulated metal door | 513.0 CNY/door-$m^2$ | 26.9 CNY/door-$m^2$ |

* 1 CNY = 0.14 EUR.

Considering the lifespan of the renovation materials, the maintenance and renewal cost was not considered in this study. The residual value was assumed to be 37.5% of the original material cost of individual renovation measures [31]. The prices of raw coal and electricity are 0.150 CNY/kWh and 0.510 CNY/kWh, with $CO_2$ emission factors of 0.312 kg $CO_2$/kWh and 0.584 kg $CO_2$/kWh, respectively [23,32–34]. The nominal interest rate used in the calculation is 4.75%/a [35]. The escalation rate of energy price is +0.8%/a for coal and electricity [36].

Three optimized solutions were selected, which were named $CO_2$ emissions-optimal renovation solution, cost-optimal renovation solution, as well as a typical solution from the Pareto-front. Since earlier studies often applied the requirements from the Chinese design standard of newly built rural houses [19] to form the renovation designs, solutions based on this standard were also compared with optimized solutions, as well as pre-renovation cases.

## 3. Results

The results presented in this section include the main results of SBMO analysis under applying intermittent and continuous heating modes. The comparison was then conducted between the pre-renovation case, the standard-based solutions and three chosen optimized solutions. Among them, the cost-optimal solutions were retained for a more extensive comparison with the pre-renovation case, analyzing the differences between intermittent and continuous heating modes and their impacts on envelope renovation.

### *3.1. Results of SBMO Analysis*

After performing optimization, only the solutions from the Pareto-front are presented in Figure 5. Three kinds of optimized solutions on the Pareto-front were selected and are highlighted; these were $CO_2$ emissions-optimal (renovation solution 1), cost-optimal (renovation solution 3) and one typical optimized solution between the previous two solutions (renovation solution 2). In addition, the pre-renovation cases and the standard-based solutions are also presented in Figure 5, Tables 5 and 6. Two different heating modes, intermittent and continuous heating, were applied separately. Intermittent heating mode simulated the original schedule of the case building, where Kang system and coal boiler ran 15 h and 6 h every day, respectively. While in continuous heating mode, the coal boiler was regulated to operate 24 h every day at a heating setpoint of 14 °C. The red shapes in Figure 5 represent the solutions with intermittent heating, whereas the blue ones are with continuous heating.

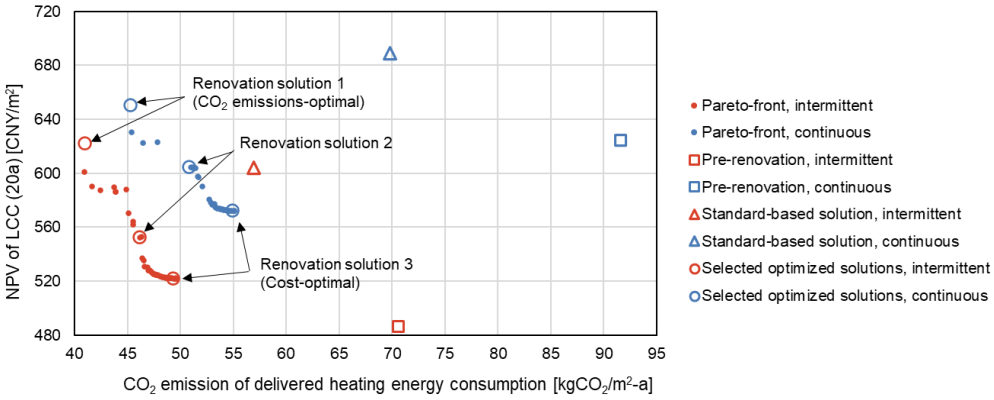



**Figure 5.** The annual $CO_2$ emissions and lifecycle cost for optimized and standard-based renovation solutions with different heating modes.

Under the intermittent heating mode in Table 5, it should be mentioned that the case building has a significantly low NPV of LCC of 486.3 CNY/$m^2$ before the renovation, and this value is less than all renovation options. The standard-based solution cuts the $CO_2$ emissions of delivered energy consumption by 19%, from 70.6 kg $CO_2$/$m^2$-a to 56.9 kg $CO_2$/$m^2$-a, while its NPV of LCC increases by 24%, from 486.3 CNY/$m^2$ to 604.2 CNY/$m^2$. The $CO_2$ emissions can be further reduced by optimized renovation solutions 2 and 3, with less LCC than the standard-based solution as well. Renovation solution 1 could minimize the $CO_2$ emissions to 40.9 kg $CO_2$/$m^2$-a, showing a 42% decrease compared with the pre-renovation case. However, a significant gain in LCC (28%) should also be noted. Renovation solution 3 has the minimum LCC in all renovation solutions, which is still 7% higher than the pre-renovation case, while its $CO_2$ emissions could be remarkably reduced by 30%.

**Table 5.** Comparison of pre-renovation cases and renovation solutions under intermittent heating mode.

| | Pre-Renovation | Standard-Based Solution | Renovation Solution 1 ($CO_2$ Emissions-Optimal) | Renovation Solution 2 | Renovation Solution 3 (Cost-Optimal) |
|---|---|---|---|---|---|
| Wall insulation thickness of southern external walls (mm) | 0 | 38 | 187 | 172 | 169 |
| Thermal transmittance of southern external walls ($W/m^2K$) | 0.92 | 0.50 | 0.18 | 0.19 | 0.19 |
| Wall insulation thickness of other external walls (mm) | 0 | 38 | 141 | 179 | 141 |
| Thermal transmittance of other external walls ($W/m^2K$) | 0.92 | 0.50 | 0.22 | 0.18 | 0.22 |
| Ground floor insulation thickness (mm) | 0 | 0 | 185 | 166 | 28 |
| Thermal transmittance of ground floor ($W/m^2K$) | 3.15 (bedrooms); 3.88 (other rooms) | 3.15 (bedrooms); 3.88 (other rooms) | 0.16 | 0.17 | 0.84 |
| Glazing type | Original windows | Option 2 | Option 1 | Original windows | Original windows |
| Thermal transmittance of windows ($W/m^2K$) | 2.30 | 2.00 | 1.48 | 2.30 | 2.30 |
| $CO_2$ emissions of delivered energy consumption (kg $CO_2/m^2$-a) | 70.6 | 56.9 | 40.9 | 46.1 | 49.3 |
| NPV of LCC (20a) ($CNY/m^2$) | 486.3 | 604.2 | 622 | 552.6 | 522 |

**Table 6.** Comparison of pre-renovation cases and renovation solutions under continuous heating mode.

| | Pre-Renovation | Standard-Based Solution | Renovation Solution 1 ($CO_2$ Emissions-Optimal) | Renovation Solution 2 | Renovation Solution 3 (Cost-Optimal) |
|---|---|---|---|---|---|
| Wall insulation thickness of southern external walls (mm) | 0 | 38 | 187 | 188 | 200 |
| Thermal transmittance of southern external walls ($W/m^2K$) | 0.92 | 0.50 | 0.18 | 0.18 | 0.17 |
| Wall insulation thickness of other external walls (mm) | 0 | 38 | 141 | 200 | 168 |
| Thermal transmittance of other external walls ($W/m^2K$) | 0.92 | 0.50 | 0.22 | 0.17 | 0.19 |
| Ground floor insulation thickness (mm) | 0 | 0 | 185 | 55 | 49 |
| Thermal transmittance of ground floor ($W/m^2K$) | 3.15 (bedrooms); 3.88 (other rooms) | 3.15 (bedrooms); 3.88 (other rooms) | 0.16 | 0.48 | 0.53 |
| Glazing type | Original windows | Option 2 | Option 1 | Option 2 | Original windows |
| Thermal transmittance of windows ($W/m^2K$) | 2.30 | 2.00 | 1.48 | 2.00 | 2.30 |
| $CO_2$ emissions of delivered energy consumption (kg $CO_2/m^2$-a) | 91.6 | 69.8 | 45.3 | 50.9 | 54.9 |
| NPV of LCC (20a) ($CNY/m^2$) | 624.5 | 688.8 | 650.6 | 604.6 | 572.2 |

Under continuous heating mode, it can be clearly observed in Figure 5 that all the optimized solutions on Pareto-front exceed the standard-based solution in terms of both environmental and financial aspects. It is illustrated in Table 6 that the standard-based renovation cuts $CO_2$ emissions by 24%, but with a sacrifice of higher LCC, rising to 688.8 CNY/$m^2$. After lifting 4% of LCC, renovation solution 1 decreases the $CO_2$ emissions to a minimum value of 45.3 kg $CO_2$/$m^2$-a, which is dramatically 51% lower than the pre-renovation case. Renovation solutions 2 and 3 can achieve fewer $CO_2$ emissions and lower LCC simultaneously. Renovation 3 not only dramatically reduces $CO_2$ emissions by 40% compared with the pre-renovation case, but also helps reduce the LCC more (8%) than renovation solution 2 (3%).

It is demonstrated that in the case of intermittent heating, the LCC of standard-based solution exceeds that of renovations 2 and 3. In the continuous heating circumstance, it is higher than all optimized solutions on Pareto-front. It is illustrated that renovation solution 3 (cost-optimal), regardless of the heating mode, has advantages over the standard-based solution in both economic and environmental aspects.

When the values of decision variables of different renovation measures are examined, it is found that the design standard of newly built rural houses demands windows with improved thermal performance at a higher investment cost, but no enhancement for ground floor insulation is required. Renovation solution 3, however, chooses to preserve the original windows and invest more in external wall and floor insulation. In addition, it is noticed that renovation solution 3 under continuous mode requires higher thermal performance of walls and ground floor than that under intermittent mode.

### *3.2. Comparison between Pre- and Post-Renovation Cases*

#### 3.2.1. Impact of Different Heating Modes

The next step involved comparing and analyzing every pre- and post-renovation case, while the case building was heated intermittently or continuously, respectively. The following four cases were defined:

Case 1 is a reference case that mimicked the original performance of the case building with the heating system operating intermittently.

Case 2 was simulated based on the same building envelope characteristics as Case 1, but the coal boiler operated continuously during the heating season.

Case 3 applied the same intermittent heating mode as Case 1, but it conducted the envelope renovation solution 3 (cost-optimal) designed as in Section 3.1.

Case 4 ran the coal boiler continuously as Case 2, and it also applied its renovation solution 3 (cost-optimal).

Table 7 lists the comparison results of four cases based on indoor climate, economic costs and environmental impacts.

Due to the fact that the residents spend their time mostly in two bedrooms, the indoor climate of these two rooms was analyzed. Regardless of whether a renovation is carried out or not, it is obvious that the instances with continuous heating always have higher average temperatures and lower daily temperature variations than the ones heated intermittently. In addition, the average temperature in bedroom 2 is always lower than in bedroom 1. The explanation for this is that bedroom 1 is heated by a Kang and a radiator at the same time, receiving more heat than bedroom 2, which just has a radiator for space heating. In Case 1, the two bedrooms have a large average daily temperature variation of 6.1 °C and 8.8 °C, respectively. Case 2 with continuous heating increases the average temperature in two bedrooms by 2 °C and 3.8 °C, as well as reducing the daily temperature variation by 3.2 °C and 7.3 °C, respectively. However, this improvement is achieved based on the increased yearly energy cost by 10.1 CNY/$m^2$ and $CO_2$ emissions by 21 kg $CO_2$/$m^2$-a.

The indoor $CO_2$ concentration is relatively high in bedrooms during the heating season, particularly in bedroom 1, where residents spend the majority of their time living and sleeping. After the envelope renovation, there is hardly any difference in indoor $CO_2$ concentration. This is due to the fact that the ventilation is mainly supplied through envelope

infiltration during heating season instead of manually opening windows, and its change is very limited with the changing indoor temperature. Therefore, future renovation should take into account changing the ventilation system to further improve indoor air quality.

**Table 7.** Case-based evaluation of envelope renovation and heating modes.

| | | Case 1 (Pre-Renovation with Intermittent Heating) | Case 2 (Pre-Renovation with Continuous Heating) | Case 3 (Cost-Optimal Solution with Intermittent Heating) | Case 4 (Cost-Optimal Solution with Continuous Heating) |
|---|---|---|---|---|---|
| Indoor climate | | | | | |
| Average temperature during heating season (°C) | Bedroom 1<br>Bedroom 2 | 14.1<br>10.8 | 16.1<br>14.6 | 17.4<br>13.6 | 18.6<br>15.8 |
| Average difference of daily maximum and minimum temperatures during heating season (°C) | Bedroom 1<br>Bedroom 2 | 6.1<br>8.8 | 2.9<br>1.5 | 4.7<br>6.6 | 3.8<br>2.7 |
| Average $CO_2$ level during heating season (ppm) | Bedroom 1<br>Bedroom 2 | 1989<br>1496 | 1976<br>1347 | 1908<br>1430 | 1882<br>1356 |
| Average exchange rate (ACH) | whole building, during heating season | 0.049 | 0.052 | 0.123 | 0.144 |
| | whole building, during non-heating season | 0.781 | 0.781 | 0.952 | 0.998 |
| Economic costs | | | | | |
| NPV of LCC (20a) (CNY/$m^2$) | | 486.3 | 624.5 | 522.0 | 572.2 |
| Total investment cost (CNY/$m^2$) | | 0 | 0 | 211.0 | 232.2 |
| Annual energy cost (CNY/$m^2$) | | 35.5 | 45.6 | 25.3 | 28.0 |
| Environmental impacts | | | | | |
| $CO_2$ emissions of delivered energy consumption (kg $CO_2$/$m^2$-a) | | 70.6 | 91.6 | 49.3 | 54.9 |

Generally speaking, the average air exchange rate is extremely low during the heating season, but optimized renovation measures slightly improve it. The air exchange rate is significantly higher during the non-heating season due to the use of openable windows.

#### 3.2.2. Effectiveness of Envelope Renovation on Thermal Comfort

The outcomes of applying cost-optimal renovation solutions are shown in Cases 3 and 4. Table 7 demonstrates that average temperature is enhanced no matter which heating mode is applied. When intermittent heating is used, the envelope renovation leads to an increase in average temperatures of two bedrooms by 3.3 °C and 2.8 °C, as well as a decrease in the daily temperature variations by 1.4 °C and 2.2 °C, respectively.

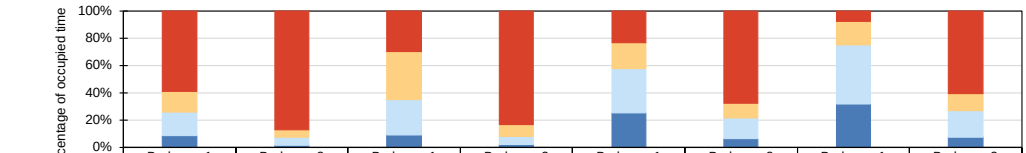
While the coal boiler is heated continuously, the average temperatures of two bedrooms only increase by 1.2 °C and 2.2 °C, respectively. This improvement is not as obvious as in the intermittent heating case. Therefore, if applying the cost-optimal envelope renovation, continuous heating has less advantage in improving the average indoor temperature if compared with applying intermittent heating.

The average PMVs in the bedrooms during the heating season in four cases are presented in Table 8. It is illustrated that before renovation, applying continuous heating could obviously improve the average PMV in bedroom 2, from −1.4 to −0.9, while bedroom 1 increased from −0.8 to −0.5 (see Cases 2 and 1). The comparison between Cases 3 and 1 shows that after conducting envelope renovation, the average PMV in bedroom 1 is improved from −0.8 to −0.4, which is better than only applying continuous heating mode. While average PMV in bedroom 2 is improved only to −1.0, not as good as the value of −0.9 in Case 2. The comparison between Cases 4 and 3 demonstrates that if switching to continuous heating mode after renovation, the average PMVs in bedrooms could be further improved to −0.2 and −0.7, respectively, which are closer to the neutral level (value of 0).

**Table 8.** Average PMVs in the bedrooms during the heating season.

| | | Case 1 (Pre-Renovation with Intermittent Heating) | Case 2 (Pre-Renovation with Continuous Heating) | Case 3 (Cost-Optimal Solution with Intermittent Heating) | Case 4 (Cost-Optimal Solution with Continuous Heating) |
|---|---|---|---|---|---|
| Average PMV level during heating season | Bedroom 1 | −0.8 | −0.5 | −0.4 | −0.2 |
| | Bedroom 2 | −1.4 | −0.9 | −1.0 | −0.7 |

Figure 6 shows the time proportions of PMV categories during the heating season. Before envelope renovation, it could be seen between Cases 2 and 1 that the continuous heating mode leads to a significantly reduced time by 29% at Level IV in bedroom 1, while the reduction in bedroom 2 is not obvious (only 4%). If analyzing the PMV improvement after renovation, Cases 3 and 1 could reflect the effectiveness of renovation when applying intermittent heating mode, where a 36% reduced time at level IV is noticed in bedroom 1 with a 20% reduction in bedroom 2. A comparison between Cases 4 and 2 with continuous heating demonstrates that bedroom 1 spends 23% less time at Level IV. Therefore, the beneficial impact of envelope renovation on PMV is more noticeable when the rural house is heated intermittently than continuously.




| | Bedroom 1 Case 1 (intermittent) | Bedroom 2 Case 1 (intermittent) | Bedroom 1 Case 2 (continuous) | Bedroom 2 Case 2 (continuous) | Bedroom 1 Case 3 (intermittent) | Bedroom 2 Case 3 (intermittent) | Bedroom 1 Case 4 (continuous) | Bedroom 2 Case 4 (continuous) |
|---|---|---|---|---|---|---|---|---|
| IV (<−0.7, >+0.7) | 59% | 87% | 30% | 83% | 23% | 67% | 7% | 60% |
| III (−0.7~+0.7) | 16% | 6% | 35% | 9% | 19% | 11% | 17% | 13% |
| II (−0.5~+0.5) | 17% | 5% | 26% | 6% | 33% | 15% | 43% | 19% |
| I (−0.2~+0.2) | 8% | 2% | 9% | 2% | 25% | 7% | 32% | 8% |

**Figure 6.** Proportions of bedroom PMVs during heating season in four categories of EN 16798-1:2019 standard [36].

According to the above results, utilizing intermittent heating is more effective than continuous heating in demonstrating the positive impacts of envelope renovation on increasing average temperature, decreasing temperature differences, and lowering occupied time at low thermal comfort levels.

## 4. Discussion

According to the Pareto-front optimization results, rural house owners might select the cost-optimal renovation option based on their personal financial situation or goals for $CO_2$ emission reduction. It is observed that when using an intermittent heating schedule, the LCC of the cost-optimal solution is still greater than before, which would have an impact on the residents' motivation to carry out the renovation. Cost is a crucial factor in determining whether the renovation project can be implemented, particularly when the renovated house is located in a rural area with limited economic levels. There are three possible solutions to this issue. Firstly, the previous study has proved that residents' desire to improve their indoor environment helps to increase their willingness to finance the renovation [37]. Therefore, the comparison results in Figure 6, which show the improvement in indoor thermal comfort, could be attractive to residents and encourage them to conduct the envelope renovation. Furthermore, the parameter combination of the cost-optimal solution reveals the renovation priority, which might be helpful if the funds are limited. It is observed that the insulation performance of the southern external walls is deemed more important than other external walls, followed by the ground floor. In either heating mode, both cost-optimal solutions decide to preserve the original windows, implying that window replacement is not as cost-effective as insulation addition. Third, this study does

not incorporate any external financial support, which is another effective approach to promoting renovation willingness. This was proven by a successful pilot renovation project in Shanghe county, in which residents bore only one-third of the total investment, with the remainder covered by government subsidies, enterprise support and bank loans [38]. With financial assistance, residents may be able to choose more "expensive" deep renovation alternatives with lower $CO_2$ emissions, which is more beneficial for the environment.

There are no guidelines for rural house renovation in this climate condition yet. Several earlier studies developed the envelope renovation plan on the premise of meeting the requirements of the design standard of newly built rural houses. However, the comparative analysis in this study shows that this approach may not be economically advantageous for renovating actions. Compared with the standard-based solutions, the optimized renovation plan has obvious potential to cut $CO_2$ emissions and lower the LCC significantly.

The optimization results reveal the significance of wall renovation. As can be seen in Tables 5 and 6, the thermal transmittance of external walls in cost-optimal solutions has improved to the level of 0.2 $W/m^2K$, which is much better than the standard-required 0.5 $W/m^2K$. This performance level (0.2 $W/m^2K$) is consistent with the wall performance values of the cost-optimal solutions in the Finnish detached house renovation project, which have similar building types and climate conditions [39].

The thermal performance of load-bearing masonry walls could be improved by using external and internal insulation. The latter approach, however, would reduce the indoor area and disturb occupants during construction. It also increases the risk of mold growth, interstitial condensation, and freeze–thaw damage [40]. To avoid these potential problems, external insulation was applied in this study. However, internal insulation would be preferable in cases where maintaining the facades is necessary or desirable, such as historic buildings or urban-context buildings [41].

Conventional materials, EPS and XPS board, were chosen for the additional insulation materials of the external walls and ground floors in this study. Galimshina et al.'s study [42] demonstrates that bio-based insulation materials, such as wood fiber, hemp mats and straw bales, have excellent moisture-buffering capacity and insulation properties. Because of the low embodied carbon and potential carbon storage, they are climate-friendly solutions. Straw boards and straw bales are also applied as insulation material in some Chinese rural houses [43]. However, due to the poor moisture and fire resistance of these materials, they are typically used in sandwich insulation or as infills of frame structures, which is not applicable to the external insulation renovation measure in this study. Other bio-based insulation materials, such as bio-aerogel thermal insulation panels [44], which can be installed on the outer surfaces of external walls, were not considered as options in this study due to their limited local accessibility and high investment costs.

It is also recommended to pay attention to the insulation needs of the ground floor. There is no similar requirement in the current building standards for newly constructed rural houses.

It should be noted that the thickness of the insulation board in the actual renovation project will not be as precise as given in Table 5 or Table 6. In order to maintain dimension control and construction viability, they are frequently produced at intervals of 5 mm or 10 mm [11]. As a result, the thickness can be selected as closely as possible to the ideal value.

Replacing original windows without altering their sizes was considered one of the renovation measures in this study. Large windows on the southern facade are a local tradition in this region, which ensures sunlight availability and increases solar heat gains in winter. Even if changing window size has a significant effect on heat demands, using the same window areas in a renovation project would be easier from a practical point of view. However, in the design of new rural houses, optimizing window size could be regarded as a considerable solution to limit heat losses.

The findings presented above could provide some guidance for the development of renovation guidelines and the implementation of future envelope renovations that have similar building and climate conditions.

Three solutions from the Pareto-front were chosen and compared in the results of SBMO analysis. Two extreme solutions ($CO_2$ emissions-optimal and cost-optimal) and one solution in the middle of Pareto-front were chosen to show the effective range of renovation measures as well as to demonstrate the differences of design variable values in different optimal solutions. In the practical renovation project, when one final renovation solution should be determined, decision-making methods, such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) or Analytical Hierarchy Process (AHP), could be utilized to comprehensively analyze the stakeholders' interests and quantify the alternatives' performance [45].

There is a degree of uncertainty in this study associated with the process of parameter tuning. Window opening and heat fuel adding is performed based on the comfort feeling of occupants with high uncertainty. The window control strategy and heating schedules were estimated in this study based on occupants' feedback, monitored indoor temperature data and the literature.

In this study, the heating setpoint temperature in rural houses was set at 14 °C with the clothing thermal resistance of rural residents in winter at 1.42 clo. The reason for using a higher value of clothing thermal resistance than the common value in the urban context is that rural residents are accustomed to wearing heavier jackets at home, which could save them heating costs while also improving the convenience of frequently entering and departing their homes to use the toilet or to pick up heat fuel in yards. The setting of low heating temperature could stem from their lower thermal expectations of indoor temperature based on their thermal history [46]. However, as rural residents' living standards improve, they may seek warmer indoor temperatures. In the future, they may aim for an increase to 18 °C, similar to that of urban apartment buildings in China [25]. In addition, future renovation may include installing indoor toilets for convenience, reducing the need to enter and exit the house. For the above causes, the thermal resistance of the clothing worn by rural residents may decrease.

It was assumed in this study that the airtightness remains the same after renovation. Improving building airtightness is also a common means of energy-saving renovation. However, the stove and boiler burn coal indoors, and residents have the habit of not opening windows in winter. Therefore, indoor air quality requires a certain amount of fresh air flow. This airflow mainly comes from envelope infiltration in cold winter. However, the ventilation rate of the studied house is still insufficient during the heating season, and the high $CO_2$ level in bedrooms also reveals this. Table 7 presents that the average $CO_2$ level in two bedrooms is higher than 1900 ppm and 1300 ppm, respectively, both of which need improvement. In addition, the toilets are now in yards, and residents take showers in public bathing centers. If toilets with showers are added to rural houses in the future renovation, it could affect both air exchange rate and moisture level, which leads to greater ventilation demand for $CO_2$ level reduction and dehumidification purposes. The renovation solutions of the ventilation system with sufficient ventilation rate would be studied in the future.

This study focused on the envelope renovation, and the original heating systems were maintained. With the purpose of conducting deeper renovation, further study may take system renovation into account, which may lead to changing the optimal solutions, as well as the effectiveness of renovation applying different heating modes. This hypothesis would be studied in future research.

## 5. Conclusions

The studied rural house represents a typical Chinese rural house located in severe cold regions. The objective of this study was to figure out the cost-optimal envelope renovation solutions for houses with different lifecycle costs and $CO_2$ emission levels. The comparison of renovation effectiveness was conducted between two heating modes, traditional intermittent heating and possible continuous heating. Simulation-based multi-optimization analysis was conducted in this study using the building simulation tool IDA ICE and its integrated optimization tool AutoMOO.

Results of the optimization analysis show that the cost-optimal renovation solutions with intermittent and continuous heating can cut $CO_2$ emissions by 30% and 40%, respectively. The LCC of the cost-optimal renovation solution with intermittent heating remains 7% greater than its pre-renovation case, while that with continuous heating can be 8% lower than its pre-renovation case. For houses using intermittent heating mode, the cost-optimal solution could reduce the $CO_2$ emissions to 49 kg $CO_2/m^2$-a. With adequate funding, the $CO_2$ emissions could be further reduced to a minimum of 41 kg $CO_2/m^2$-a. Moreover, the comparison between optimized solutions and standard-based solutions indicates that significant potentials to cut $CO_2$ emissions and decrease LCC are observed in optimized results compared to directly applying requirements from the design standard of newly built rural houses.

Results from comparing four cases before and after renovation reveal that utilizing intermittent heating is more effective than continuous heating in demonstrating the positive impacts of envelope renovation on increasing average temperature, decreasing temperature differences and lowering occupied time at low thermal comfort levels. As a result, rural houses in severe cold climate contexts, which are often heated intermittently, could benefit significantly from envelope renovation.

The findings and recommended renovation strategy of this study can be generalized to other areas with similar building performance and severe cold climate conditions, where LCC and $CO_2$ emission reductions are pursued during envelope renovations. They can also provide suggestions for future renovation guidelines for rural houses.

Further research is also recommended to explore attractive financial solutions to encourage rural house owners to carry out deeper renovations that improve the house performance with fewer $CO_2$ emissions, especially when the house is heated intermittently. Similar studies are also needed for other representative rural house prototypes with different layouts in this climate region. Furthermore, considering the current level of indoor air quality, adding more effective ventilation systems and replacing with more efficient and environmentally friendly energy systems are recommended for investigation in the future.

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