

Article

Multi-Objective Optimization with Active–Passive Technology Synergy for Rural Residences in Northern China

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Abstract: Due to the serious problems with energy efficiency, carbon emissions, and thermal comfort of rural residences in northern China, an optimization of active and passive heating technologies for rural residences is necessary. In this paper, an optimization for rural residences in northern China is conducted with four objectives: the whole life cycle carbon emission; the annual energy consumption through heating, ventilation, and air conditioning systems; the annual cost; and thermal comfort. In addition, the optimization model with active–passive heating technology synergy is resolved by NSGA-II genetic algorithm. The active and passive design variables, including the type of air source heat pump, orientation, the type and thickness of envelope insulation, the layer of window glass, the window-to-wall area ratio, as well as sunspace parameters are preferred to obtain the optimal solution. The results indicate that the optimal solution obtained by the ideal point method gives the most outstanding performance. Compared with the prototype, the optimized carbon emissions in severe cold and cold regions decreased by 56.1% and 54.6%, respectively. The annual energy consumption decreased by 59.7% and 62.2%. Finally, the roof insulation thickness is the most sensitive design variable in Pareto-optimal solution sets. This paper offers significant guidance in the application of the optimization method of active–passive technology synergy to the energy-saving design of buildings.

Keywords: multi-objective optimization; active–passive technology synergy; heating; rural residences; northern China; life cycle



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1. Introduction

With rapid economic development, energy consumption and carbon emissions are on the rise year by year. International and domestic policies have been proposed to drive energy conservation and emission reduction. The Paris Agreement was signed by 178 parties around the world. Meanwhile, the carbon peak and neutrality targets were proposed in China in 2020, aiming to peak CO₂ emissions by 2030 and reach carbon neutrality by 2060. According to the China Building Energy Consumption Research Report (2022), the energy consumption of buildings and construction accounts for 45.5% of the total, and the carbon emissions of buildings and construction account for 50.9% of the total [1]. Therefore, building energy conservation is essential to reduce carbon emissions and energy consumption.

Most of the rural residences in China are self-built [2]. The envelope insulation cannot meet the standard requirements, resulting in a high heating load [3]. Furthermore, heating relies on bulk coal combustion, leading to the problem of high energy consumption and high carbon emissions [4]. Therefore, a low-carbon transition of rural residences in northern China is an effective way to achieve the carbon peak and neutrality targets.

Passive building technology, as an effective way to reduce energy consumption, is widely used in building construction and renovation. Numerical studies have been conducted to optimize building shape coefficient, orientation, envelope, and other parameters [5]. Feng et al. argued that the best shapes for buildings were trapezoids and rectangles,

according to the lowest life cycle cost [6]. F.H. Abanda et al. analyzed the impact of different orientations on energy consumption and found that a well-orientated building could lead to significant life cycle energy savings. Namely, the difference in electricity consumption between the best and worst orientations of buildings was 17,056 kWh throughout a 30-year period [7]. Moreover, Xu et al. used a genetic algorithm to optimize the heat transfer coefficient of the building envelope to ensure indoor comfort and reduce energy consumption [8]. Hossein Atashbarr et al. optimized the building envelope materials by combining life cycle assessment with building information modeling. The results showed that the energy consumption of buildings in Iran was reduced by 40% after selecting the optimal materials for the envelope [9]. Yao et al. investigated the influence of transparent envelope parameters on daylighting, thermal comfort, and energy efficiency of rural buildings in cold regions. Compared with the prototype, the heating and cooling loads for the optimal sunspace model were reduced by 23% and 17% [10], respectively. In addition, some research has optimized multiple influencing factors of buildings and explored the combined effect on energy consumption. M.C. Ruiz et al. applied passive technology to achieve energy savings in a house in Spain. After optimizing the orientation, window–wall ratio, and insulation, the overall consumption was reduced by nearly 13% [11]. Zhao et al. conducted the multi-objective optimization of energy-saving and low-carbon buildings, taking the orientation, building materials, window height, and window-to-wall ratio as optimization decision parameters. A building optimization design method based on building information modeling (BIM) has been proposed to meet the comprehensive and diverse requirements of energy saving, daylighting, and low carbon [12]. The studies mentioned only optimized buildings by modifying single or multiple passive technology parameters. The synergy between the active and passive technologies was not considered. However, passive and active technologies work together in the process of building heating. The approaches employed in those studies may result in variances between their optimization results and the actual optimal solutions.

In terms of active heating systems in rural areas, the current clean heating technologies are gas heating, electric heating, central heating with clean coal, heating with an air source heat pump (ASHP), geothermal heating, and biomass heating [13]. The applicability of different clean heating forms in northern China has been analyzed. It can be seen that the ASHP, as a clean, efficient, and economical heating system, could be widely used with positive technical and economic effects [14]. The ASHP forms are divided into an ASHP with a tuyere, an ASHP with a radiator, and others. Hu et al. argued that the ‘coal to electricity’ heat pump system was not meant to utilize the cast-iron radiator. Compared with a small temperature difference fan coil unit, new bimetal radiator, and radiant floor heating, the system COP and average temperature of the cast-iron radiator were the lowest and the thermal comfort was also not high [15]. Furthermore, Xiao et al. compared the performance of air-to-water and air-to-air heat pump heating systems. The results showed that the air-to-air heat pump was better than the air-to-water heat pump in low-temperature operation conditions. Specifically, as the temperature dropped from 7 °C to −20 °C, the actual operation COP of the air-to-air heat pump decreased by 15.45% less than that of the air-to-water heat pump [16]. Huang et al. simulated the indoor temperature field with radiator and tuyere heating. The results indicated that the room temperature of tuyere heating was higher than that of radiator heating, but the isotherms became relatively disorganized due to the airflow disturbance [17]. In addition, due to the built-in fans, the ASHP with a tuyere produced the sensation of blowing air, which accelerated the evaporation of human sweat and produced a sensation of dryness [18]. Given the shortcomings of the above, our previous study proposed an ASHP with a direct-condensation radiant heating panel (DRHP), which used refrigerant as the heating medium and relied on natural convection and thermal radiation for heat exchange with the room. We optimized the equipment to make up for the blowing sensation caused by fans and the secondary heat exchange of the radiator to meet the thermal comfort needs of indoor personnel. The proposed system was verified as having excellent thermal stability. Under the typical heating conditions with

the condensation temperature of 40 °C and the external temperature of −7 °C, the average heat flux was 625.5 W/m². When the external temperature varied from −12 °C to 7 °C, the system COP ranged from 2.2 to 4.0 [19–21]. Thus, the ASHP with a DRHP can be applied to the heating of rural residences in northern China.

The above research was conducted independently for active and passive heating technologies. Optimization through a combination of active and passive heating technologies has received more and more attention. Wu et al. established a multi-objective optimization model for zero-energy buildings in different climate regions. According to the results, it is possible for high-rise residential buildings in hot summer and warm winter areas, as well as mild areas, to reach zero energy consumption. It can be accomplished with the lowest photovoltaic replacement rates of 101% and 133%. In addition, nearly zero energy consumption could be accomplished in cold and hot summer areas as well as cold winter areas, with maximum rates of 89% and 84% [22]. Chen et al. developed an integrated building optimization model with the objectives of life cycle costs, whole-life carbon emissions, and indoor discomfort hours. The optimal equilibrium solution was validated to improve building performance by 13.9% [23]. In building optimization research, addressing the relationship between active and passive systems is worthy of attention. Wang et al. used the passive-simulation-optimization-active method to decrease the rural building energy consumption. They developed a passive heating design method of on-top sunspace, installed the solar water heating system, and optimized the glazing-to-roof ratio and the angle of the roof. The optimized average temperature of the building was 14.75 °C [24]. Adriana Ciardiello et al. conducted a phased optimization for a case building in the Mediterranean climate. The results indicated that the geometry optimization could save 60% of the annual energy consumption, and the passive and active systems could save 23% of the annual energy cost [25]. Furthermore, Wang et al. proposed a hierarchical collaborative optimization model. The results showed that the optimal life cycle costs and energy consumption were effectively reduced by 1948 CNY/m² and 2292 kWh/m² in a railway passenger station in the Qinghai–Tibet plateau [26]. However, the sequential optimization method did not consider the correlation between active and passive systems, resulting in some deviations between the optimization results and the actual optimal solutions [27]. Xu et al. proposed a multi-objective coordinated optimization method for school buildings that trade off energy, life cycle cost, daylighting, and thermal comfort. The results showed that the life cycle cost of the optimal solution was 2.75% less than the multi-stage optimization [28]. Chen et al. constructed a co-optimization model with the objective of minimum carbon emissions and selected active–passive solar heating buildings in some typical areas of Tibet for optimization analysis. Compared with passive buildings heated with boilers, the optimized carbon emissions of active and passive technologies could be decreased by 26.5–50.3% [27].

In order to have a clearer understanding of the related advanced methods, typical studies on multi-objective optimization of buildings in recent years are summarized and drawn in Table 1.

To sum up, the optimization of active and passive systems in buildings has tended to meet the comprehensive requirements of environmental protection, energy saving, economy, and thermal comfort. In addition, the optimization method with active–passive technology synergy can accurately reflect the synergistic relationship between active and passive techniques to avoid deviations between the optimization results and the actual optimal solutions. However, there is little research on the application of multi-objective optimization with active–passive technology synergy in rural residences at present.

Therefore, this paper uses Energy Plus to model active and passive heating systems in rural residences. A multi-objective optimization model with active–passive technology synergy is established to comprehensively optimize the whole life cycle carbon emission, the annual operating energy consumption of the HVAC system, the annual cost, and thermal comfort (TC). The NSGA-II genetic algorithm is used to solve the optimization model. This paper takes a typical two-story rural residence in northern China as an example to obtain optimal solutions for active and passive design parameters including orientation,

window-to-wall area ratio, insulation type and thickness, and sunspace. Sensitivity analysis of each design variable to the four objective functions is conducted. The research results have guidance significance to the heating design of rural residences in cold and severe cold regions.

Table 1. Recent research on building optimization.

Year	Authors	Objectives	Optimization Variables	Optimization Algorithms
2020	Wang et al. [26]	Energy consumption Total cost	Building envelope Window-to-wall ratio Active heating system	NSGA-II
2020	Iván García Kerdan et al. [29]	Energy destructions Thermal comfort Life cycle cost	Building envelope HVAC system Photovoltaic arrangement Wind utilization	NSGA-II
2020	Adriana Ciardiello et al. [25]	Energy demand Energy cost Investment cost Carbon emissions	Geometry Building envelope	aNSGA-II
2021	Feng et al. [6]	Energy consumption Life cycle cost	Building shape Building envelope	IMRFOA
2022	Yao et al. [10]	Daylighting Energy efficiency Thermal comfort	Building envelope Sunspace	SPEA-II
2022	Zhao et al. [12]	Carbon emissions Energy consumption Daylighting	Orientation Window-to-wall ratio Window height Building materials	NSGA-II
2022	Wu et al. [22]	Annual energy demand Total power generation Investment cost	Orientation Window-to-wall ratio Heat transfer coefficient Photovoltaic system	NSGA-II
2022	Xu et al. [28]	Energy Thermal comfort Daylighting Life cycle cost	Building envelope Photovoltaic arrangement External window Shading	NSGA-II
2023	Xu et al. [8]	Thermal comfort Energy consumption	Heat transfer coefficient	GA
2023	Hossein Atashbar et al. [9]	Energy consumption Global warming potential	Building envelope materials	NSGA-II
2023	Chen et al. [23]	Life carbon emissions Life cycle costs Indoor discomfort hours	Building envelope HVAC system Internal gain	NSGA-II NSGA-III C-TAEA
2024	Zhan et al. [30]	Occupant comfort Life cycle carbon emissions Building cost	Building envelope Photovoltaic arrangement	NSGA-II NSGA-III C-TAEA

2. Research Method

2.1. Research Object

2.1.1. Typical City Meteorological Data

The northern regions of China are divided into a severe cold region and a cold region. The outdoor temperatures in winter in the two regions are significantly different, so the active and passive technical optimal solutions are most likely to be different. Consequently,

this paper selects Changchun and Tianjin, typical cities in the severe cold region and cold region, respectively, as research targets.

Figure 1 illustrates the monthly data of outdoor temperature and solar radiation for a typical meteorological year in Changchun and Tianjin. The standard weather data are from Energy Plus. Changchun is situated in the Grade III area of solar energy resources. From October to April, the monthly solar radiation is above 2.5 kWh/m^2 with a maximum of 7.6 kWh/m^2 , and the average outdoor dry bulb temperature is lower than 10°C with a minimum of -28.1°C . Tianjin is also situated in the Grade III area. From November to March, the monthly solar radiation is above 2.8 kWh/m^2 with a maximum of 5.1 kWh/m^2 , and the average outdoor dry bulb temperature is lower than 10°C with a minimum of -13.9°C .

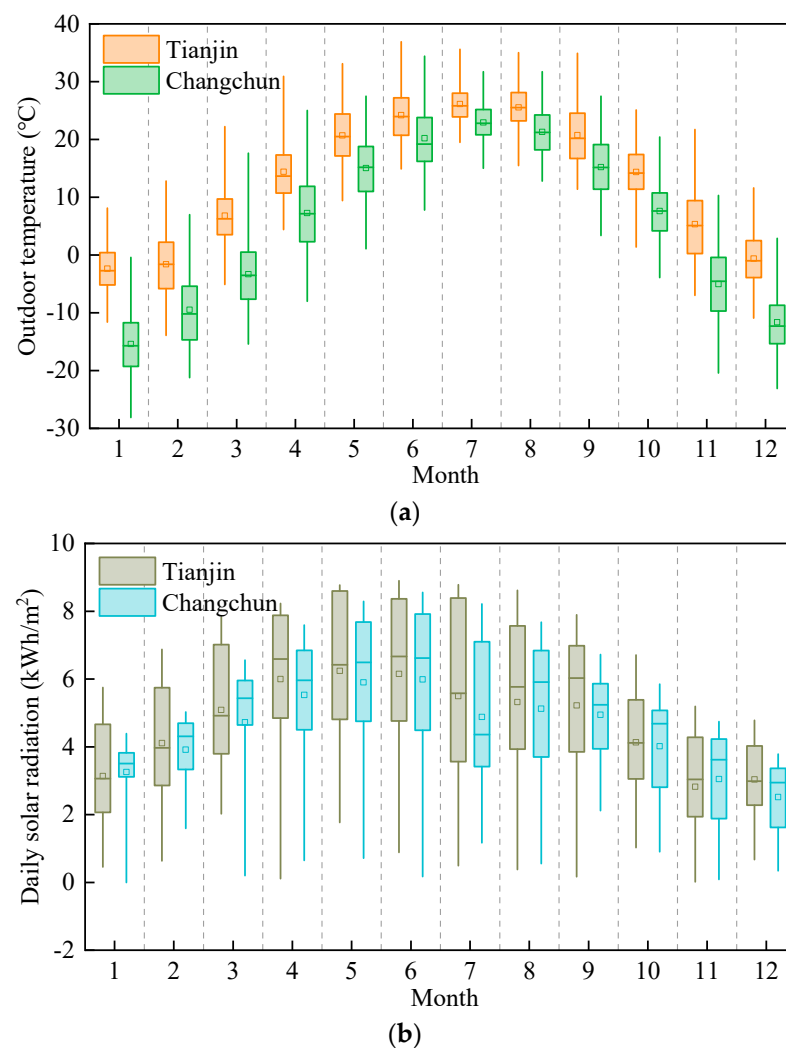


Figure 1. The climatic characteristics of a typical meteorological year. (a) Outdoor temperature; (b) daily solar radiation.

2.1.2. Residential Building Information

The prototype model is built based on the survey results from the field investigation of the current situation of rural residences in northern China. The building has two floors with a total area of 144 m^2 and it includes a living room, a kitchen, two bathrooms, three bedrooms, and a stairwell. The three-dimensional view and plan layout of the prototype model are shown in Figure 2.

The envelope parameters are shown in Table 2.

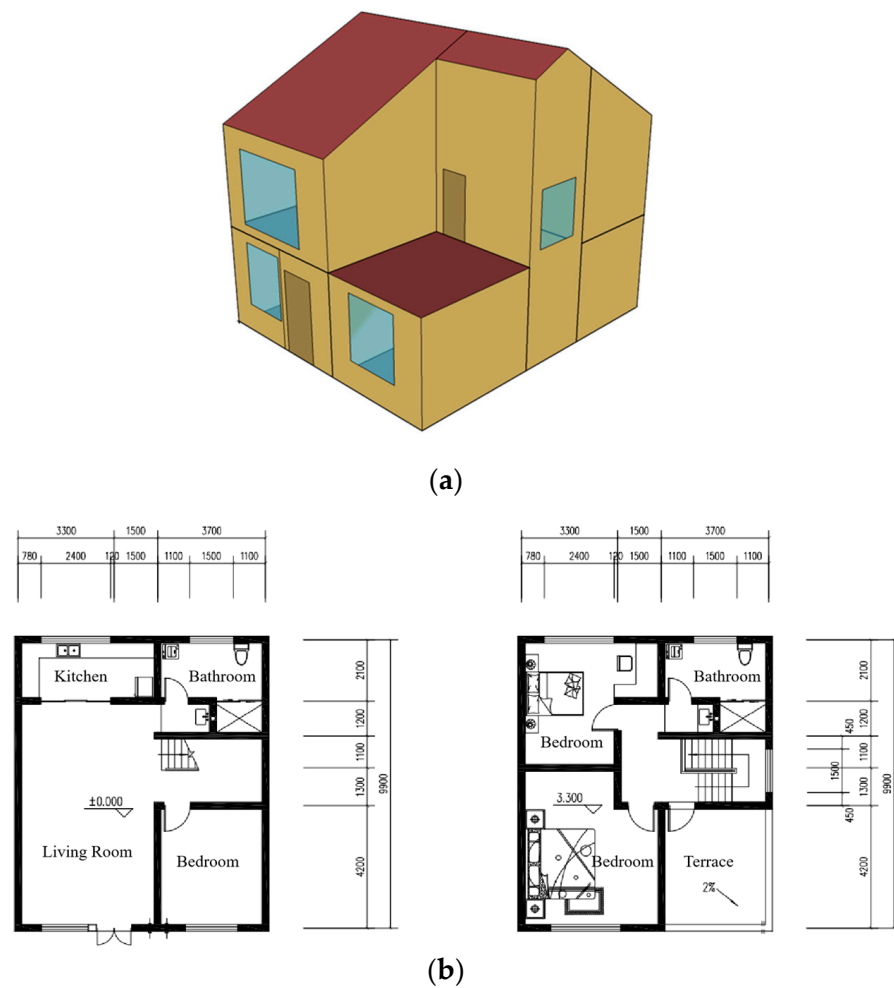


Figure 2. Prototype model. (a) Stereogram; (b) first and second floor plan.

Table 2. Envelope parameters [31].

(a) Envelope Structure Parameters		
Type of Envelope	Envelope Structure (Outside to Inside)	
External Wall	20 mm composite mortar + 10 mm XPS (insulation layer) + 240 mm coal gangue porous brick + 20 mm composite mortar	
Roof	20 mm composite mortar + 10 mm XPS (insulation layer) + 50 mm expanded perlite + 120 mm reinforced concrete + 20 mm composite mortar	
Floor	20 mm composite mortar + 10 mm XPS (insulation layer) + 120 mm reinforced concrete + 20 mm composite mortar	
Floorboard	20 mm composite mortar + 50 mm XPS (insulation layer) + 120 mm reinforced concrete + 20 mm composite mortar	
Interior Wall	20 mm composite mortar + 240 mm coal gangue porous brick + 20 mm composite mortar	
Door	10 mm iron sheet + 30 mm wood chipboard + 10 mm iron sheet	
Exterior Window	South	6 mm single-layer plate glass (bridge-cutoff aluminum alloy), window–wall area ratio is 0.16
	North	6 mm single-layer plate glass (bridge-cutoff aluminum alloy), window–wall area ratio is 0.23
	East	6 mm single-layer plate glass (bridge-cutoff aluminum alloy), window–wall area ratio is 0.03

Table 2. Cont.

(b) Envelope Structure Parameters				
Type of Envelope		Heat Transfer Coefficient W/(m ² ·K)	Solar Heat Gain Coefficient	Remarks
External Wall		0.117	—	—
Roof		0.691	—	
Floor		1.708	—	
Floorboard		0.518	—	
Interior Wall		0.122	—	
Door		1.597	—	
Exterior Window	South	5.778	0.862	The area ratio of the window frame and hole is 0.15.
	North	5.778	0.862	
	East	5.778	0.862	

The basic operating parameters of rural residences are set according to the Design Standard for the Energy Efficiency of Rural Residential Buildings [31]. These are shown in Table 3.

Table 3. Basic operating parameters.

Room	Winter Room Temperature (°C)	Ventilation Times (h ^{−1})	Number of People	Lighting Power Density (W/m ²)	Equipment Power Density (W/m ²)	Heating Period
Living room	14	0.5	3	7	3.8	Changchun: 20 October to 6 April Tianjin: 1 November to 31 March
Bedroom	14	0.5	2	7	3.8	
Kitchen	14	0.5	1	7	3.8	
Bathroom	14	0.5	1	7	0	
Stairwell	14	0.5	1	7	0	

2.2. Multi-Objective Optimization Model with Active–Passive Technology Synergy

2.2.1. Optimization Objectives

The objective functions of rural residence heating optimization in this study contain the whole life cycle carbon emission, the annual operating energy consumption of the HVAC system, the annual cost, and the ranking value of thermal comfort (TC).

$$\min \{C_{nz}, E_{yx}, M_A, TC\} \quad (1)$$

(1) Whole life cycle carbon emissions

The rationale for the whole life cycle carbon emissions is to apply the life cycle assessment (LCA) to building carbon emissions. In this paper, the whole life cycle is divided into the building materials production and transportation phase, the construction phase, the operation phase, and the demolition phase [32–34]. The equation for the whole life carbon emission is:

$$C_{nz} = C_{sc} + C_{ys} + C_{jz} + C_{yx} + C_{gy} + C_{cc} \quad (2)$$

where C_{sc} is carbon emissions from building material production, kgCO₂e; C_{ys} is carbon emissions from building material transportation, kgCO₂e; C_{jz} is carbon emissions from construction phase, kgCO₂e; C_{yx} is HVAC system operating carbon emissions, kgCO₂e; C_{gy} is HVAC system's own inherent carbon emissions, kgCO₂e; and C_{cc} is carbon emissions from demolition phase, kgCO₂e.

Carbon emissions from the production and transportation of building materials are reflected by carbon emission factors. The specific equations are [35]

$$C_{sc} = \sum_{i=1}^n G_i P_i \quad (3)$$

$$C_{ys} = \sum_{i=1}^n G_i D_i Y_i \quad (4)$$

where G_i is the consumption of the building material, m^3 ; P_i is the production carbon emission factor of the building material, $kgCO_2e/m^3$; D_i is the average transportation distance of the building material, km, with concrete taking 40 km and other building materials taking 500 km [35]; Y_i is the carbon emission factor per unit weight of transportation distance under the transportation mode of the building material, $kgCO_2e/(t \cdot km)$, with medium-sized gasoline truck transport taking $0.115 kgCO_2e/(t \cdot km)$ [35].

The carbon emission equation for the construction phase is [35]

$$C_{jz} = \sum_{i=1}^n E_{jz,i} EF_i \quad (5)$$

where $E_{jz,i}$ is the total energy consumption during the construction phase, $kW \cdot h$; and EF_i is the carbon emission factor of energy, $kgCO_2e/kW \cdot h$.

However, due to the lack of primary data on carbon emissions in this phase, we chose the carbon emission estimation equation for the construction phase [34]

$$C_{jz} = (X + 1.99) A_b \quad (6)$$

where X is the number of floors; and A_b is the building area, m^2 .

When calculating carbon emissions in the operation phase of rural residences, this study only considers the HVAC system, including inherent and operational carbon emissions [32].

$$C_{yx} = y \sum_{i=1}^n E_i EF_i \quad (7)$$

$$C_{gy} = C_{yx} Z_{sys} \quad (8)$$

where E_i is the annual energy consumption, $kW \cdot h/a$; y is building design life, taking 50 years; Z_{sys} is the system's own inherent carbon emission conversion factor, with the ASHP system taking 0.05 [36].

The carbon emission equation for the demolition phase is [35]

$$C_{cc} = \sum_{i=1}^n E_{cc,i} EF_i \quad (9)$$

where $E_{cc,i}$ is the total energy consumption during the construction phase, $kW \cdot h$.

However, due to the lack of primary data on carbon emissions, we refer to the law summarized in Zhao's literature [34]. The carbon emissions of the demolition phase are taken as 10% of those of the construction phase:

$$C_{cc} = 0.1 C_{jz} \quad (10)$$

(2) The annual energy consumption of the HVAC system

$$E_{yx} = \sum_{d \in D} E_{yx,d} \quad (11)$$

where d is HVAC system operation days; D is HVAC system operation days collection; and $E_{yx,d}$ is the energy consumption for the HVAC system on the d th operation day, kWh.

(3) The annual cost

The annual cost calculation includes the initial investment's present value and the HVAC system's total operating cost for the heating season.

$$M_A = M_{ic} + M_{zyx} \quad (12)$$

The present value of the initial investment is calculated as follows:

$$M_{ic} = (M_{gz} + M_{ys} + M_{jcaz} + M_{qt} + M_{ktic}) \times \frac{r(1+r)^y}{(1+r)^y - 1} \quad (13)$$

where M_{gz} is the purchase of building materials, USD; M_{ys} is the transportation cost of building materials, USD; M_{jcaz} is the installation cost of building materials, USD; M_{qt} is other construction requirements, USD, generally in the range of 139–278 USD/m² [26]; M_{ktic} is the HVAC system initial investment, USD; r is the discount rate, taking 7%.

$$M_{gz} = \sum_{i=1}^n G_i M_i \quad (14)$$

$$M_{ys} = d_{ys} M_{gz} \quad (15)$$

$$M_{jcaz} = d_{jcaz} M_{gz} \quad (16)$$

$$M_{ktic} = M_{in} + M_{ktaz} = \sum_{i=1}^n P_{in,j} \times \varphi_j + d_{ktaz} \sum_{i=1}^n P_{in,j} \times \varphi_j \quad (17)$$

where M_i is the unit price of material i , USD; d_{ys} is the construction material transportation cost conversion factor; d_{jcaz} is the building material installation cost conversion factor; M_{ktaz} is the HVAC installation cost, USD; M_{in} is the HVAC system initial investment, USD; $P_{in,j}$ is the acquisition cost per unit capacity, USD/kW; φ_j is the capacity of HVAC equipment, kW; d_{ktaz} is the HVAC installation cost conversion factor, which is 2.5% of the acquisition cost.

The HVAC system's total operating cost for the heating season is calculated as follows:

$$M_{zyx} = M_{wh} + M_{yx} = d_{wh} M_{in} + \sum_{\Delta u \in \Phi} E_e(\Delta u) D_e(\Delta u) \quad (18)$$

where M_{wh} is the HVAC maintenance cost, USD; M_{yx} is the HVAC operating cost, USD; d_{wh} is the HVAC maintenance cost conversion factor, with ASHP taking 8% [26]; $E_e(\Delta u)$ is the HVAC system energy consumption during the Δu period, kWh; $D_e(\Delta u)$ is the HVAC system tariff during Δu period, USD/kWh; Φ is the HVAC system electricity consumption time collection in the heating season.

(4) Thermal comfort ranking value

A lower HVAC equipment comfort ranking value represents a higher comfort level. This paper introduces the TC level of two HVAC systems: the ASHP with a tuyere and the ASHP with DRHP. The system constructions are shown in Figure 3.

The main difference between the two ASHPs is the type of heat transfer with indoor air. The ASHP with a tuyere has built-in fans. The refrigerant in the condenser mainly relies on forced convection heat transfer to release heat. However, it has problems with an air-blowing sensation and indoor noise pollution [18]. The ASHP with a DRHP depends on natural convection and heat radiation for heat exchange with indoor air. The vertical channels were hexagonal in cross-section, in which the refrigerant copper pipe was arranged. Water was injected into the gap between the vertical channels and the copper pipe as a heat storage material to provide heat for the defrosting condition. Interconnected straight and round composite ribs were arranged on the back of each panel to strengthen the natural

convection with indoor air [37]. Referring to the experimental test results of indoor thermal comfort with the DRHP in our previous studies [38], it finds that compared with the ASHP with a tuyere, the DRHP provides better indoor thermal comfort. When using the ASHP with a DRHP for heating, the predicted mean vote (PMV), and the predicted percentage dissatisfied (PPD) as well as the local dissatisfaction rates caused by the vertical temperature difference and the floor surface temperature (LPD2, LPD3) can meet the requirements of the International Thermal Comfort Standard Class II. Compared with the ASHP with a tuyere, the indoor average horizontal and vertical temperature differences are reduced by 1–2 °C when using the ASHP with a DRHP for heating. Therefore, the ASHP with a DRHP can reduce the body temperature difference to avoid the discomfort of the head overheating and the feet chilling. In summary, the TC of the ASHP with a DRHP is 1, and the TC of the ASHP with a tuyere is 2.

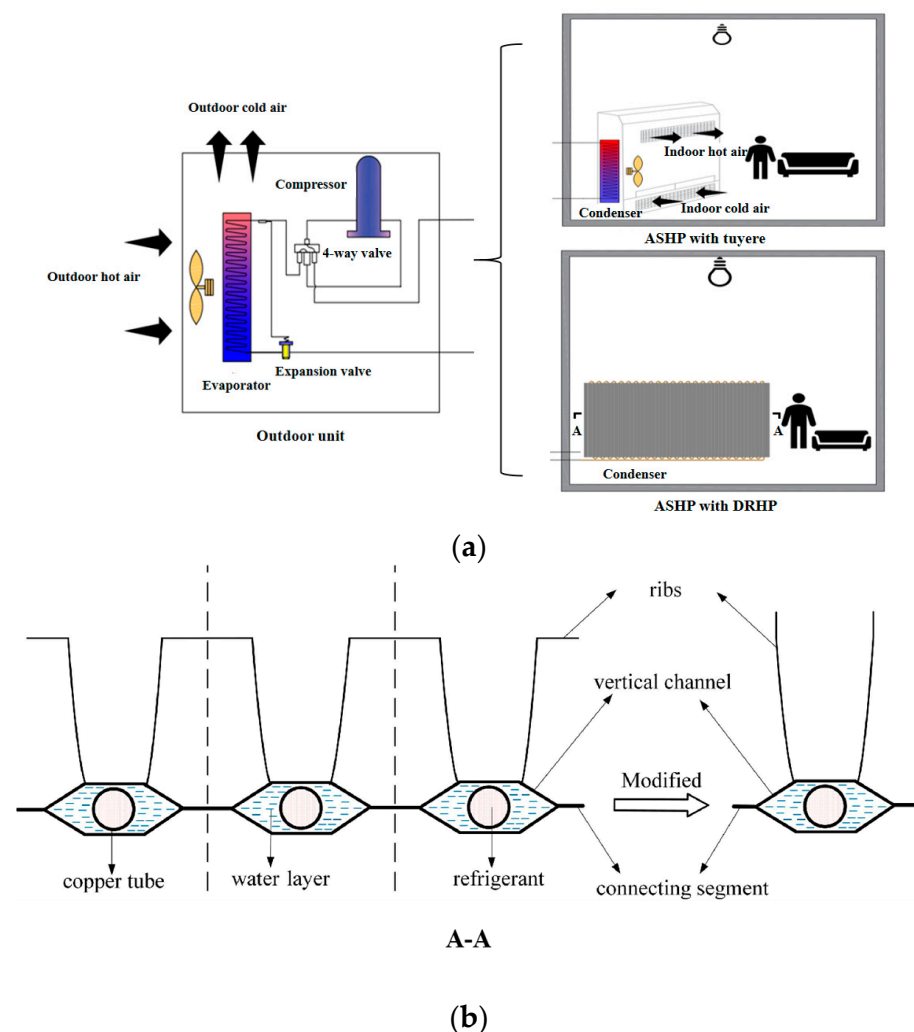


Figure 3. System construction of ASHP heating system. (a) System construction of ASHP heating system; (b) cross-section of DRHP [37] (The cross section at position A-A in (a)).

2.2.2. Objective Function Calculation Parameters

In order to calculate the objective functions, the following parameters are set with consideration of market conditions. The carbon emission factors and unit prices of the envelope materials are shown in Table 4. The costs of HVAC equipment are shown in Table 5. The unit prices and carbon emission factors of electric heating are shown in Table 6.

Table 4. Carbon emission factor and unit price of envelope material [35].

Envelope Material	Carbon Emission Factor (kgCO ₂ e/Unit1)	Unit1	Unit Price (USD/Unit2)	Unit2	Density (kg/m ³)
Composite mortar	13	m ³	57.2	t	1700
Coal gangue porous brick (240 × 115 × 53 mm)	16	m ³	0.07	block	1400
Reinforced concrete	496	m ³	123	m ³	2500
Iron sheet	2400	t	1736	t	7250
Wood chipboard	336	m ³	833	m ³	200
XPS	3290	t	111	m ³	25
EPS	3130	t	55.6	m ³	18
Expanded perlite	1980	t	208	t	80
6 mm LowE glass	0.88	kg	13.2	m ²	2500
6 mm plate glass	0.76	kg	9.4	m ²	2500
Bridge-cutoff aluminum alloy window	194	m ²	2.6	kg	2690

Table 5. Economic parameters of HVAC equipment.

Equipment	Initial Investment (USD/kWh)	Maintenance Cost
ASHP with tuyere	132	8% of initial investment
ASHP with DRHP	139	

Table 6. Electric heating price and carbon emission factor [39].

City	Time Frame	Electricity Price (USD/kWh)	Carbon Emission Factor (tCO ₂ e/MWh)
Changchun	Peak	8:00–21:00	0.5703
	Valley	21:00–8:00 next day	
Tianjin	All day	0.071	

2.2.3. Design Variables

For the selection of design variables for an active heating system, this paper focuses more on the problem of heating optimization with active–passive technology cooperation. The design variables considered in this paper are the types of active heating systems.

In the passive design optimization, the design parameters are divided into three types:

- The parameters that can be adjusted at the design stage, such as the orientation and window–wall area ratio, which can affect the energy consumption of rural residences.
- The parameters that can be modified when rural residences are in use, such as the thickness of the envelope insulation layer, which can affect the heat transfer coefficient of the envelope.
- Passive energy-saving technology, such as the design of sunspace, which can play a role in reducing energy demand.

Considering the influence of the above design parameters on the optimal objective function of rural residences, the passive design variables considered in this study and their value ranges are compiled in Table 7.

Table 7. Design variables and value ranges.

Design Variable		Symbol	Value Range
Main body	Orientation	O_b	-30° – 30° , step size 10°
	Window-to-wall area ratio on south elevation	WR_{south}	0.25–0.40, step size 0.05 (Changchun) 0.25–0.45, step size 0.05 (Tianjin)
	Window-to-wall area ratio on north elevation	WR_{north}	0.10–0.25, step size 0.05 (Changchun) 0.10–0.30, step size 0.05 (Tianjin)
	South wall insulation type	g_{ws}	1:XPS/2:EPS
	South wall insulation thickness	d_{ws}	0.00–0.40 m, step size 0.01 m
	North wall insulation type	g_{wn}	1:XPS/2:EPS
	North wall insulation thickness	d_{wn}	0.00–0.40 m, step size 0.01 m
	East wall insulation type	g_{we}	1:XPS/2:EPS
	East wall insulation thickness	d_{we}	0.00–0.40 m, step size 0.01 m
	West wall insulation type	g_{ww}	1:XPS/2:EPS
	West wall insulation thickness	d_{ww}	0.00–0.40 m, step size 0.01 m
	Roof insulation type	g_r	1:XPS/2:EPS
	Roof insulation thickness	d_r	0.00–0.40 m, step size 0.01 m
	Floor insulation type	g_g	1:XPS/2:EPS
	Floor insulation thickness	d_g	0.00–0.40 m, step size 0.01 m
Sunspace	Glass type	W_s	1: 6 mm Lowe glass/ 2: 6 mm plate glass
	Number of glass layers	W_n	1/2/3
	Depth	L_{yg}	0.6–1.5 m, step size 0.3 m
	Window-to-wall area ratio	WR_{yg}	0.6–0.9, step size 0.1
	Glass lamination thickness	d_h	0.003–0.024 m, step size 0.003 m

2.2.4. Multi-Objective Optimization Algorithm

Based on the statistics of the usage frequency of different optimization algorithms in more than two hundred pieces of building optimization research provided by SciVerse Scopus from Elsevier, it is found that genetic algorithms are most commonly used in architectural optimization [40,41]. Among the representative genetic algorithms, the non-dominated sorting genetic algorithm II (NSGA-II) can search for solutions with different tradeoffs in the Pareto frontier through nondominated sorting and congestion distance calculation, helping make optimal decisions. The NSGA-II algorithm has the advantages of simple arithmetic, high speed of convergence, high computational accuracy, good robustness, and high dependability [42,43], but it has the limitations of search space and constraints processing ability [44,45]. However, with the mature computational process and high accuracy, the algorithm performs well in dealing with multi-objective problems and is frequently applied to architectural multi-objective optimization [26,46]. In this paper, the NSGA-II algorithm is used for multi-objective optimization with active–passive technology synergy. The specific process is shown in Figure 4.

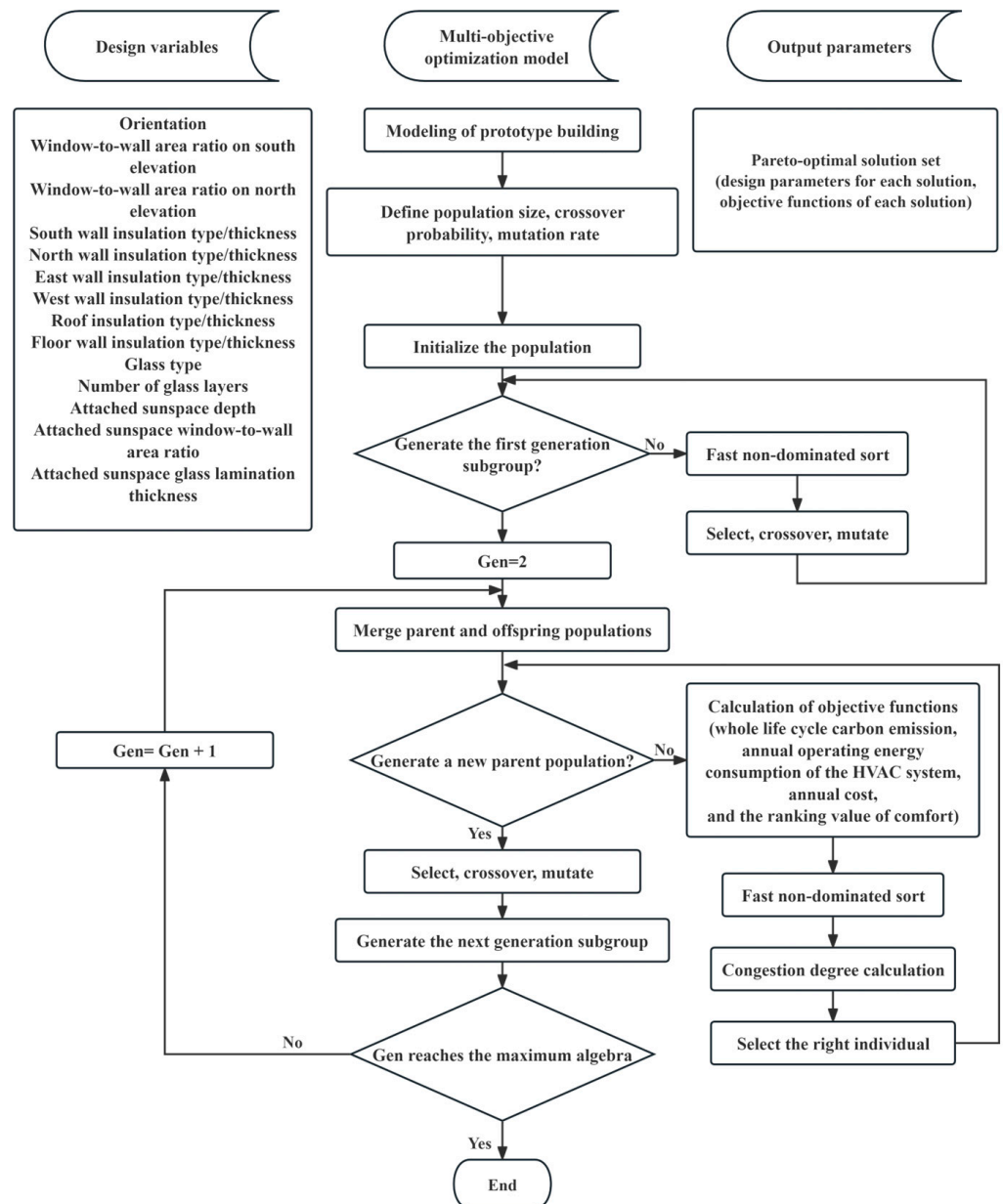


Figure 4. Multi-objective optimization process.

3. Results and Discussion

3.1. Multi-Objective Optimization Results Analysis in Changchun

The multi-objective optimization solution set of rural residence heating in Changchun is shown in Figure 5. There is an overall negative correlation between the annual cost and the whole life cycle carbon emission, as well as the annual operating energy consumption of the HVAC system, but a positive correlation between the annual operating energy consumption of the HVAC system and the whole life cycle carbon emission.

Figure 6 shows the distribution of each objective function in the Pareto-optimal solution set. The whole life cycle carbon emission is distributed between 177.90 tCO₂e and 211.57 tCO₂e, with an average value of 186.36 tCO₂e. The whole life cycle carbon emission of the prototype is 458.18 tCO₂e, as shown in Figure 7. The average reduction after optimization is 59.3%. The annual energy consumption of the HVAC system is distributed between 4605.88 kWh and 6084.78 kWh, with an average value of 5047.27 kWh, and the annual energy consumption of the HVAC system in the prototype is 14,128.35 kWh, as shown in Figure 7. The average reduction after optimization is 64.3%. The annual cost is

distributed between 4182 USD and 4925 USD, with an average value of 4482 USD, while the annual cost of the prototype is 4494 USD, which is reduced by 0.03% after optimization. The comfort ranking value TC is 1. It indicates that the ASHP with a DRHP is selected for each solution, and the thermal comfort is improved.

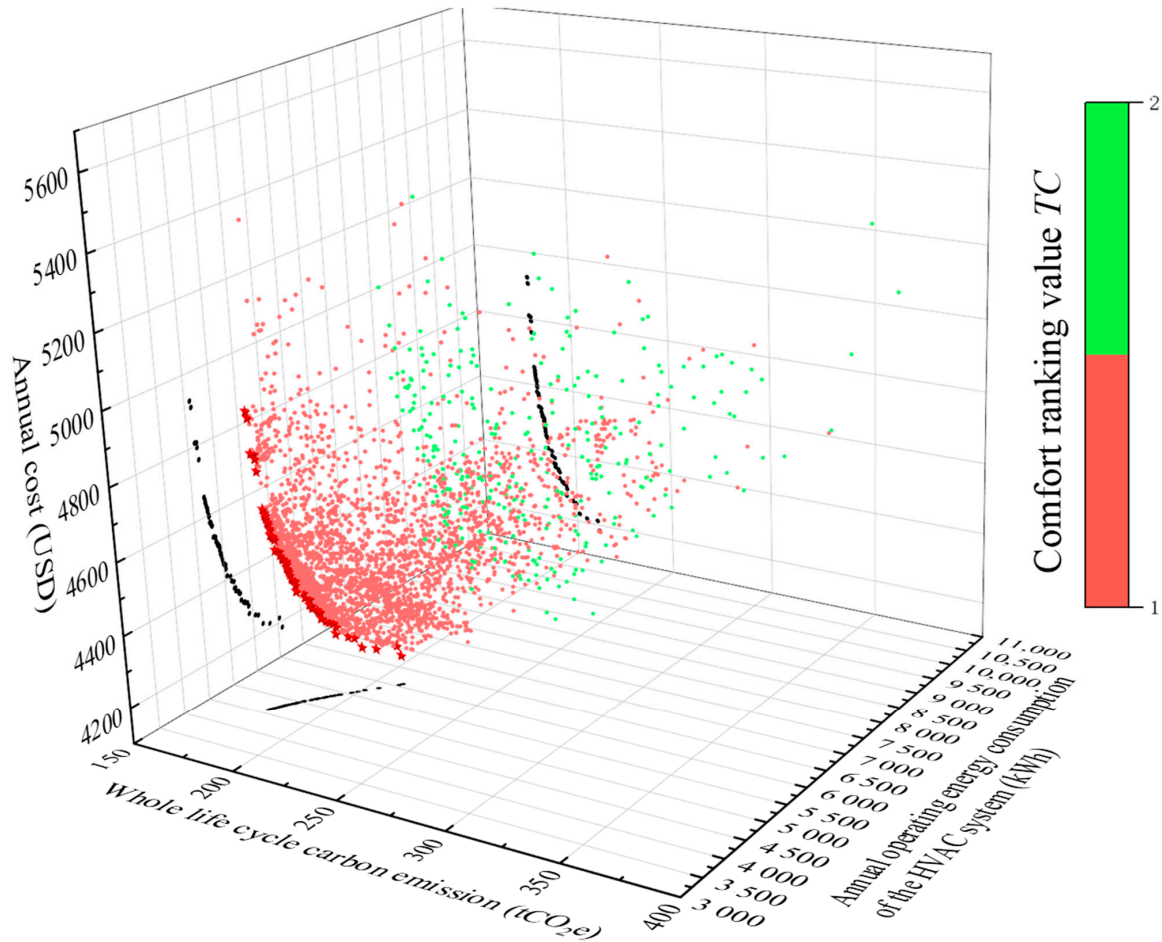


Figure 5. Multi-objective optimization solution set in Changchun.

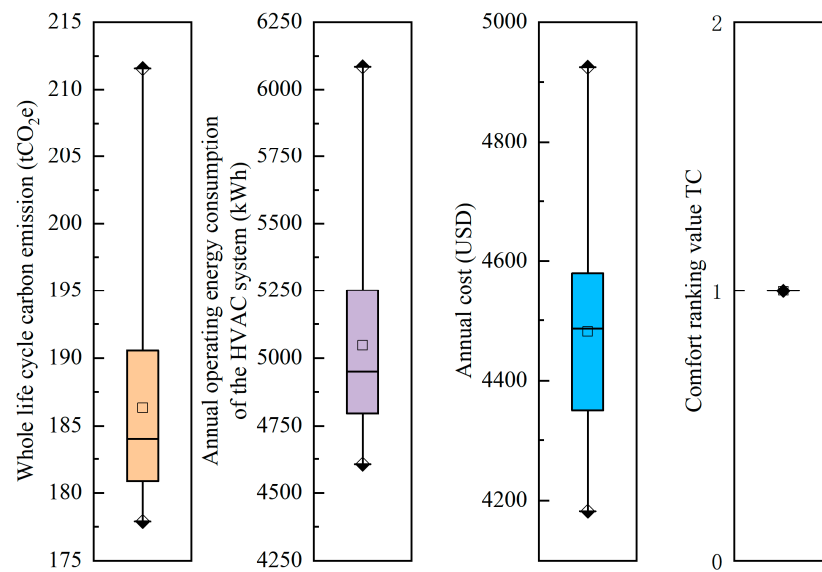


Figure 6. Distribution of each objective function in Changchun.

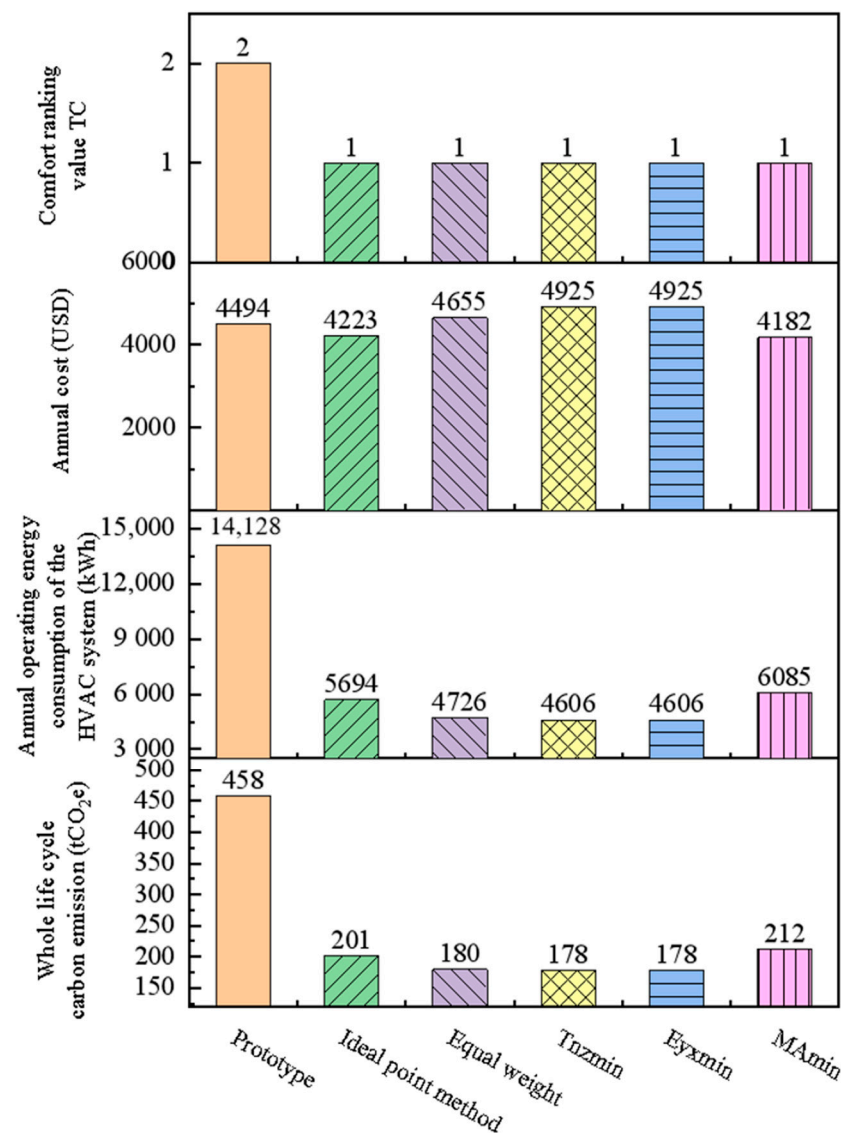


Figure 7. Values of each objective function obtained via different decision methods in Changchun.

In this paper, the ideal point method and the linear weighted sum method are used for decision-making. In the decision-making with the linear weighted sum method, four types of weights are assigned, namely a case of equal weights, a case of the minimum whole life cycle carbon emission, a case of the minimum annual operating energy consumption of the HVAC system, and a case of the minimum annual cost. Figure 7 shows the values of each objective function in the optimal results with decision-making.

Compared with the prototype, the optimal results obtained by several decision-making methods show the same performance of 1 in terms of comfort ranking value. The ASHP with a DRHP is adopted to improve indoor comfort. However, the performance in other objective functions is different. From the perspective of the whole life cycle carbon emission, the results obtained by each decision-making method are ranked as $T_{nzmin} = E_{yxmin} < \text{Equal weight} < \text{Ideal point method} < M_{Amin} < \text{Prototype}$. From the perspective of annual operating energy consumption of the HVAC system, the order of the results is $E_{yxmin} = T_{nzmin} < \text{Equal weight} < \text{Ideal point method} < M_{Amin} < \text{Prototype}$. The order of the annual cost of the results is $M_{Amin} < \text{Ideal point method} < \text{Prototype} < \text{Equal weight} < T_{nzmin} = E_{yxmin}$.

The difference between the optimal solutions obtained by each decision-making method is analyzed. The M_{Amin} method is to adjust the orientation to the east, choose economical insulation materials for the envelope, increase the thickness of the insulation layer,

and adjust the window-to-wall area ratio and the glass lamination thickness of the sunspace. The overall increase in the cost of passive technical is less than the decrease in the cost of active technical, which is more economical than the prototype. The two decision methods, T_{nzmin} and E_{yxmin} , reduce the thermal load of rural residences by continuing to deflect the orientation to a greater angle and adjusting the insulation materials and thickness of the envelope. It in turn significantly reduces the operating energy consumption and carbon emission of the active heating system and performs better in the whole life carbon emission and the annual operating energy consumption of the HVAC system. However, the increase of passive design parameters is greater than the reduction in the cost generated by the active technology, making both perform worse in terms of economics than other decision methods. The realization of a decision-making method with equal weights tends to the T_{nzmin} and E_{yxmin} methods, which is still less economical than the prototype. The results of the ideal point method are more favorable to the M_{Amin} method. Compared with the M_{Amin} method, higher insulation performance is achieved at the expense of better economy by increasing the thickness of the insulation layer. Thus, the energy consumption of the HVAC system is reduced. The increase of carbon emission associated with passive technology is less than the reduction of carbon emission associated with active technology, resulting in less whole-life carbon emission and lower than that of the prototype. From all perspectives, the optimal solution obtained by the ideal point method gives the best performance.

The comparison of the optimization results of the ideal point method with the prototype in Changchun is shown in Table 8. Compared with the prototype, the optimal result obtained by the ideal point method increases the initial investment in passive technology by 10.1%. However, the annual cost decreases by 6.0% due to the substantial reduction of the initial investment in active technology and annual operation and maintenance cost, which is better in terms of economy. From the perspective of eco-friendliness, both passive and active technology-related carbon emissions are significantly reduced, resulting in a reduction of 56.1% in the whole life cycle carbon emission. From the energy-saving perspective, the HVAC system's annual energy consumption is reduced by 59.7%. From the perspective of thermal comfort, the ASHP with a DRHP is used as the solution. In summary, the performance of the optimal solution obtained by the ideal point method is better than that of the prototype in all four objective functions.

Table 8. Comparison of optimization results by ideal point method in Changchun.

	Parameter	Unit	Prototype	Ideal Point Method	Difference Percentage
Economy	Passive Technology Initial Investment	USD	44,914	49,460	10.1%
	Active Technology Initial Investment	USD	2379	1917	−19.4%
	Total Initial Investment	USD	47,293	51,378	8.6%
	Operation and Maintenance Cost	USD	1067	501	−53.1%
	Annual Cost	USD	4494	4223	−6.0%
Environmental Protection	Passive Technology Carbon Emission	tCO ₂ e	45.0	34.7	−22.9%
	Active Technology Carbon Emission	tCO ₂ e	413.1	166.5	−59.7%
	Total Carbon Emission	tCO ₂ e	458.2	201.2	−56.1%
Energy Efficiency	Annual Operating Energy Consumption	kWh	14,128.4	5693.9	−59.7%
Thermal Comfort	TC Ranking Value	—	2	1	—

3.2. Multi-Objective Optimization Results Analysis in Tianjin

The multi-objective optimization solution set of rural residence heating in Tianjin is shown in Figure 8. The correlations among the objective functions are consistent with the results in Changchun.

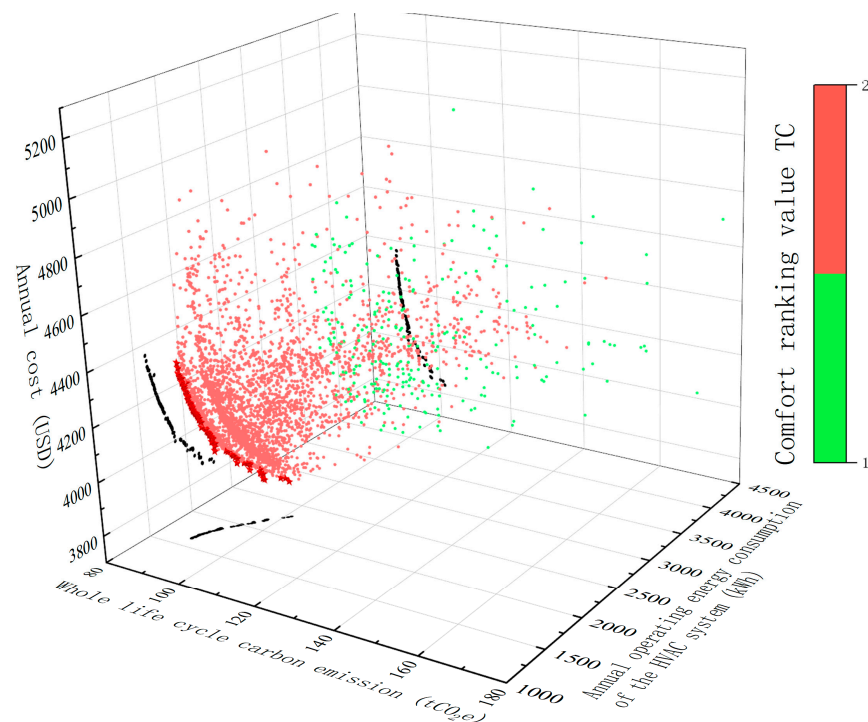


Figure 8. Multi-objective optimization solution set in Tianjin.

Figure 9 shows the distribution of each objective function in the Pareto-optimal solution set. The whole life cycle carbon emission ranges from 88.61 tCO₂e to 101.29 tCO₂e, with an average value of 91.46 tCO₂e. The whole-life carbon emission of the prototype is 223.31 tCO₂e, as shown in Figure 10. The average reduction after optimization is 59.0%. The annual energy consumption of the HVAC system of the Pareto-optimal solution is distributed between 1626.06 kWh and 2304.73 kWh, with an average value of 1838.37 kWh. The annual energy consumption of the HVAC system of the prototype is 6096.86 kWh. The average reduction after optimization is 69.8%. The annual cost is distributed between 3837 USD and 4360 USD, with an average value of 4119 USD, while the annual cost of the prototype is 3898 USD, with an average increase of 5.7% after optimization. The comfort ranking value TC is 1, indicating that the ASHP with a DRHP is adopted for each solution in the Pareto solution concentration, and thermal comfort is improved.

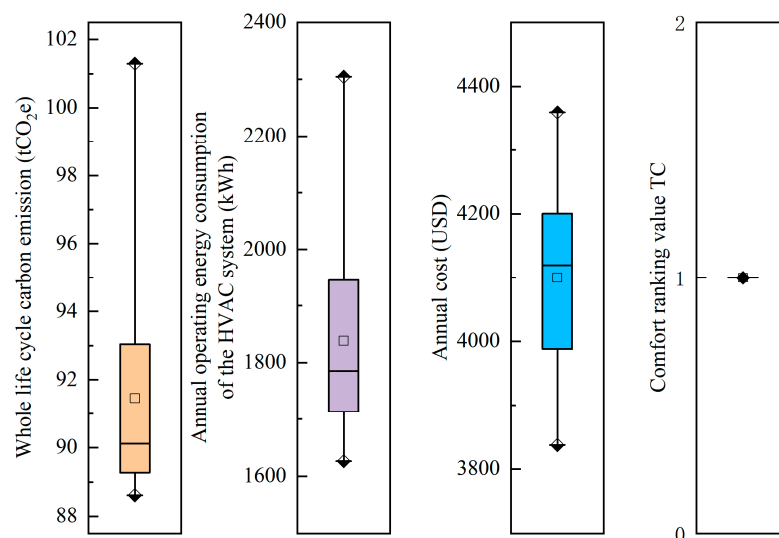


Figure 9. Distribution of each objective function in Tianjin.

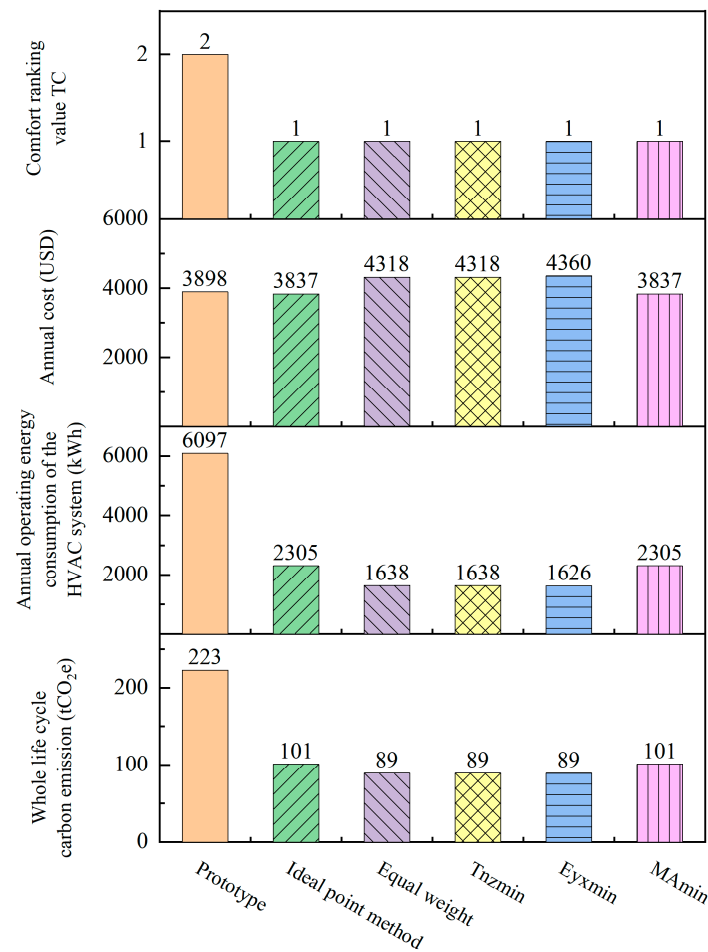


Figure 10. Values of each objective function obtained by different decision methods in Tianjin.

The decision-making method of the multi-objective Pareto-optimal solution set for rural residences in Tianjin is the same as that in Changchun. Figure 10 shows the values of each objective function in the optimal results with decision-making.

The optimal results obtained by several decision-making methods are the same as those in Changchun, and the comfort ranking value TC is 1. From the perspective of the whole life cycle carbon emission, the results of each decision-making method are ranked as $T_{nzmin} = \text{Equal weight} < E_{yxmin} < \text{Ideal point method} = M_{Amin} < \text{Prototype}$. From the perspective of the annual energy consumption of the HVAC system, the order of the results is $E_{yxmin} < T_{nzmin} = \text{Equal weight} < \text{Ideal point method} = M_{Amin} < \text{Prototype}$. The results of annual cost are ranked as $M_{Amin} = \text{Ideal point method} < \text{Prototype} < T_{nzmin} = \text{Equal weight} < E_{yxmin}$.

By increasing the thickness of the exterior wall and roof insulation and adjusting the window-to-wall area ratio of the south elevation of the sunspace, the M_{Amin} method makes the increase in the passive technology cost less than the reduction in the active technology cost, which is more economical than the prototype. The T_{nzmin} method increases the thickness of the envelope insulation layer and increases the window-to-wall area ratio of the south elevation of the sunspace to achieve better insulation performance. The increase of carbon emission related to passive technology is less than the decrease of carbon emission related to active technology, resulting in the lowest whole life cycle carbon emission. However, the increase in passive technology cost is more significant than the decrease in active technology cost, so the economy is poor compared with the prototype. The E_{yxmin} method increases the insulation layer thickness to reduce the thermal load, which in turn significantly reduces the operational energy consumption and carbon emission of the active heating system. Nevertheless, the increase in the cost of passive design input is more

significant than the reduction in the cost of the HVAC system, so the economic performance is worse. The optimal solution obtained by the decision-making method with equal weights is consistent with the T_{nzmin} method and stands out in terms of environmental friendliness. In addition, the ideal point method is more beneficial than the M_{Amin} method, which is outstanding in terms of economy.

The optimal results obtained from the ideal point method are used as an example to compare with the prototype.

The comparison of the optimization results of the ideal point method with the prototype in Tianjin is shown in Table 9. Compared with the prototype, the optimal results obtained by the ideal point method increase the initial investment in passive technology by 7.6%. However, the annual cost is reduced by 6.8% due to the reduction of initial investment in active technology as well as annual operation and maintenance costs. The carbon emissions associated with passive and active technology are reduced by 24.7% and 62.2%, respectively, resulting in a 54.6% reduction in the whole life cycle carbon emission. The annual energy consumption of the HVAC system is reduced by 62.2%, which is better in terms of energy saving. Regarding thermal comfort, the ASHP with a DRHP gives better performance. In summary, the optimal solution obtained by the ideal point method performs better than the prototype in all four objectives.

Table 9. Comparison of optimization results by ideal point method in Tianjin.

	Parameter	Unit	Prototype	Ideal Point Method	Difference Percentage
Economy	Passive Technology Initial Investment	USD	44,914	48,342	7.6%
	Active Technology Initial Investment	USD	1405	1138	−19.0%
	Total Initial Investment	USD	46,319	49,480	6.8%
	Operation and Maintenance Cost	USD	542	252	−53.4%
	Annual Cost	USD	3898	3837	−1.5%
Environmental Protection	Passive Technology Carbon Emission	tCO ₂ e	45.0	33.9	−24.7%
	Active Technology Carbon Emission	tCO ₂ e	178.3	67.4	−62.2%
	Total Carbon Emission	tCO ₂ e	223.3	101.3	−54.6%
Energy Efficiency	Annual Operating Energy Consumption	kWh	6096.9	2304.7	−62.2%
Thermal Comfort	TC Ranking Value	—	2	1	—

3.3. Comparison of Optimization Results between Two Regions

In the Pareto-optimal solution set space in Changchun and Tianjin, the optimal solutions are obtained by using the ideal point method for decision-making. The whole life cycle carbon emission, the annual operation energy consumption of the HVAC system, and the annual cost of the optimal solution in Tianjin are only 50.3%, 48.8%, and 90.9% of that in Changchun, respectively. The comfort ranking value TC of both is 1. A comparison of the optimization results in these two regions is shown in Table 10.

In the optimization results of Changchun and Tianjin, the sunspace depth is 0.6 m (the lower limit of the value range) so that the heat dissipation and the consumption of building materials are reduced while obtaining solar radiation through the sunspace. The economic performance of EPS is better, and the material is used for buildings in Changchun and Tianjin, but its thermal insulation property is not perfect. Three-layer insulating glass is used to reduce heat transfer. The window-to-wall area ratio of the north elevation is 0.1 (the lower limit of the value range) to reduce heat dissipation while ensuring lightness. The window-to-wall area ratio of the south elevation is raised to the upper limit of the range to obtain as much solar radiation as possible in these two scenarios. The thickness of glass lamination in the sunspace is 0.015 m to reduce heat dissipation. The ASHP with a DRHP is adopted by these two regions. The increase in heating cost does not significantly impact the annual cost, but the comfort level is improved.

However, the thickness of the insulation layer used in Changchun is more significant than that in Tianjin due to the lower outdoor temperature. Compared with Tianjin, the orientation of the buildings in Changchun is shifted to the east at a greater angle, so that solar radiation can be obtained earlier in the morning. The window-to-wall area ratio of the sunspace on the south elevation in Changchun is also larger than that in Tianjin. Because the total daily radiation in Changchun in winter is lower than that in Tianjin, it is necessary to obtain solar radiation by a larger window-to-wall area ratio.

Table 10. Multi-objective optimization results in these two regions.

Parameter			Changchun	Tianjin
Sunspace Depth		m	0.6	0.6
Orientation		°	20	10
Insulation Type	North Exterior Wall		EPS	EPS
	South Exterior Wall		EPS	EPS
	East Exterior Wall		EPS	EPS
	West Exterior Wall		EPS	EPS
	Roof		EPS	EPS
	Floor		EPS	EPS
Insulation Thickness	North Exterior Wall	m	0.11	0.08
	South Exterior Wall	m	0.06	0.01
	East Exterior Wall	m	0.05	0.04
	West Exterior Wall	m	0.06	0.01
	Roof	m	0.19	0.14
	Floor	m	0.13	0.01
Glass Type			6 mm Plate Glass	6 mm Plate Glass
Number of Glass Layers			3	3
Window-to-wall Area Ratio	North Elevation		0.1	0.1
	South Elevation		0.4	0.45
	South Elevation of Sunspace		0.7	0.6
Glass Lamination Thickness of Sunspace		m	0.015	0.015
ASHP Type			ASHP with DRHP	ASHP with DRHP
Whole Life Cycle Carbon Emission		tCO ₂ e	201.2	101.3
Annual Operating Energy Consumption of HVAC System		kWh	4725.5	2304.7
Annual Cost		USD	4223.4	3837.4
Comfort Ranking Value TC			1	1

3.4. Sensitivity Analysis

In this paper, the standardized regression coefficient (SRC) is chosen as an evaluation index to assess the influence of each variable on the objective functions. In the sensitivity analysis performed in this paper, independent variables with SRC absolute values larger than 0.15 are considered sensitive. The SRC value is calculated with the following equation:

$$SRC = \beta \frac{\sigma_x}{\sigma_y} \quad (19)$$

where β is the regression coefficient; σ_x is the standard deviation of the independent variable; and σ_y is the standard deviation of the dependent variable.

The main design variables affecting objective functions in the whole solution set space of the multi-objective optimization for both regions and their sensitivity are shown in Table 11.

Table 11. Sensitivity analysis of each objective function in the whole solution set space.

	Changchun	Tianjin
Whole Life Cycle Carbon Emission	Glass lamination thickness of sunspace $d_h >$ Roof insulation thickness $d_r >$ Number of glass layers $W_n >$ Type of active heating system $Z_{HVAC} >$ Window-to-wall area ratio on north elevation WR_{north}	Roof insulation thickness $d_r >$ Type of active heating system $Z_{HVAC} >$ Number of glass layers W_n
Annual Energy Consumption of HVAC System	Glass lamination thickness of sunspace $d_h >$ Roof insulation thickness $d_r >$ Number of glass layers $W_n >$ Type of active heating system $Z_{HVAC} >$ Window-to-wall area ratio on north elevation WR_{north}	Roof insulation thickness $d_r >$ Type of active heating system $Z_{HVAC} >$ Number of glass layers W_n
Annual Cost	Glass lamination thickness of sunspace $d_h >$ Floor insulation thickness $d_g >$ West wall insulation thickness $d_{ww} >$ East wall insulation thickness $d_{we} >$ Roof insulation type $g_r >$ Attached sunspace depth L_{yg}	East wall insulation thickness $d_{we} =$ Floor insulation thickness $d_g >$ West wall insulation thickness $d_{ww} >$ Roof insulation type $g_r >$ Roof insulation thickness $d_r >$ North wall insulation thickness $d_{wn} >$ Attached sunspace depth $L_{yg} >$ East wall insulation thickness g_{we}
TC Ranking Value	Type of active heating system Z_{HVAC}	

From the perspective of the whole solution set space, the main design variables affecting four objective functions in these two regions are roughly the same, but there are some differences. For example, there are more design variables affecting the whole life cycle carbon emission and the annual operating energy consumption of the HVAC system in Changchun than that in Tianjin. In particular, the glass thickness lamination of the sunspace is the most sensitive design variable for these three objective functions of the whole life cycle carbon emission, the annual HVAC system energy consumption, and the annual cost in Changchun. While obtaining solar radiation through the sunspace, the heat transfer coefficient is reduced by adjusting the glass lamination thickness of the sunspace, thereby reducing the heat transfer to the outdoors and the heat demand. It reduces the investment related to the active heating system so that the increase of the passive technology investment is less than the reduction of the active technology investment. The above three objective functions can be reduced.

The main design variables affecting objective functions in the Pareto-optimal solution set space and their sensitivity are shown in Table 12. Since the comfort ranking value of each solution is 1 in the Pareto-optimal solution set space of both regions, the sensitivity is not discussed anymore.

Table 12. Sensitivity analysis of each objective function in the Pareto-optimal solution set space.

	Changchun	Tianjin
Whole Life Cycle Carbon Emission	Roof insulation thickness $d_r >$ North wall insulation thickness $d_{wn} >$ West wall insulation thickness d_{ww}	Roof insulation thickness d_r
Annual Energy Consumption of HVAC System	Roof insulation thickness $d_r >$ North wall insulation thickness $d_{wn} >$ West wall insulation thickness d_{ww}	Roof insulation thickness $d_r >$ North wall insulation thickness d_{wn}
Annual Cost	Roof insulation type $g_r >$ East wall insulation thickness $d_{we} >$ Floor insulation thickness $d_g >$ South wall insulation thickness d_{ws}	Floor insulation thickness $d_g >$ Roof insulation thickness $d_r >$ East wall insulation thickness $d_{we} >$ West wall insulation thickness d_{ww}

In the Pareto-optimal solution space of both regions, the main factors affecting each objective function are concentrated on the envelope insulation thickness. In particular, the

roof insulation thickness is the most sensitive design variable. With the increase in roof insulation thickness, the values of these three objective functions decrease.

4. Conclusions

In this paper, an optimization model with the synergy of active and passive technologies is established with the objectives of the whole life cycle carbon emission, annual energy consumption of the HVAC system, annual cost, and thermal comfort. The type of ASHP, orientation, envelope parameters, and attached sunspace parameters are simulated and optimized. This paper takes a typical two-story rural house in severe cold and cold regions as an example to obtain optimal solutions. Sensitivity analysis of each design variable to objective functions is conducted. The following conclusions are drawn.

General conclusions:

- From the standpoints of economy, energy efficiency, environmental friendliness, and thermal comfort, the optimal solution for rural residences derived from the ideal point method is preferred to the linear weighted sum method in severe cold and cold regions.
- In the Pareto-optimal solution set, the roof insulation thickness is the most sensitive design variable in the whole life cycle carbon emission, the annual energy consumption of the HVAC system, and the annual cost of rural residences. The objective function values decrease as the increase of roof insulation thickness.

Specific conclusions:

- Compared with the prototype, the optimized carbon emissions of rural residences in severe cold and cold regions are decreased by 56.1% and 54.6%, respectively. The annual operating energy consumption is decreased by 59.7% and 62.2%. The optimized annual cost is decreased by 6.0% and 6.8%. Moreover, the thermal comfort is improved.
- Compared with the optimal solutions, the whole life cycle carbon emission, the annual energy consumption of the HVAC system, and the annual cost of rural residences in the cold region are 50.3%, 48.8%, and 90.9% of that in the severe cold region.
- Compared to the cold region, the orientation of the rural residence in the severe cold region is shifted eastward by 10°. The window-to-wall area ratio on the south elevation of the sunspace and the thickness of the envelope insulation are increased.

Due to the limitations of software and time, this paper can be improved in the following aspects. In terms of the selection of active heating system variables, this paper only considers a limited number of active heating system types. In future work, more active heating system types can be added for heating optimization, such as solar air collectors, to make full use of renewable energy for heating and building low-carbon rural residences. In addition, this paper simplifies the whole-life carbon emission calculation method due to software limitations. In future work, we aim to explore more refined calculation methods and utilize more advanced software. It will subsequently be co-simulated with the energy consumption simulation software to enhance the accuracy of the calculation.

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

Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
ASHP	Air Source Heat Pump
DRHP	Direct-Condensation Radiant Heating Panel
HVAC	Heating, Ventilation and Air Conditioning
NSGA	Nondominated Sorting Genetic Algorithm
IMRFOA	Improved Manta-Ray Foraging Optimization Algorithm
SPEA	Strength Pareto Evolutionary Algorithm
GA	Genetic Algorithm
TAEA	Two-Archive Evolutionary Algorithm
TC	Thermal Comfort
LCA	Life Cycle Assessment
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
SRC	Standardized Regression Coefficient

Symbols

C	carbon emission, kgCO ₂ e
E	energy consumption, kWh/a
M	annual cost, USD
G	consumption of building material, m ³
P	production carbon emission factor, kgCO ₂ e/m ³
D	average transportation distance, km
Y	carbon emission factor per unit weight of transportation distance, kgCO ₂ e/(t·km)
X	number of floors
A	area, m ²
y	building design life, a
EF	energy carbon emission factor, kgCO ₂ e/kW·h
Z	inherent carbon emission conversion factor
φ	capacity
d	cost conversion factor

Superscripts

$_{nz}$	Whole life
$_{sc}$	Building material production
$_{ys}$	Building material transportation
$_{yx}$	HVAC system operation
$_{gy}$	HVAC system own
$_{cc}$	Demolition phase
$_{jz}$	Construction phase
$_i$	Building material
$_b$	Building
$_{sys}$	System
$_A$	Annual
$_{ic}$	Initial investment
$_{gz}$	Building materials
$_{jcaz}$	Installation
$_{qt}$	Other requirements
$_{wh}$	HVAC maintenance

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