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Passive Optimization Design Based on Particle Swarm Optimization in Rural Buildings of the Hot Summer and Warm Winter Zone of China

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Received: 14 November 2017; Accepted: 6 December 2017; Published: 13 December 2017

Abstract: The development of green building is an important way to solve the environmental problems of China's construction industry. Energy conservation and energy utilization are important for the green building evaluation criteria (GBEC). The objective of this study is to evaluate the quantitative relationship between building shape parameter, envelope parameters, shading system, courtyard and the energy consumption (EC) as well as the impact on indoor thermal comfort of rural residential buildings in the hot summer and warm winter zone (HWWZ). Taking Quanzhou (Fujian Province of China) as an example, based on the field investigation, EnergyPlus is used to build the building performance model. In addition, the classical particle swarm optimization algorithm in GenOpt software is used to optimize the various factors affecting the EC. Single-objective optimization has provided guidance to the multi-dimensional optimization and regression analysis is used to find the effects of a single input variable on an output variable. Results shows that the energy saving rate of an optimized rural residence is about 26–30% corresponding to the existing rural residence. Moreover, the payback period is about 20 years. A simple case study is used to demonstrate the accuracy of the proposed optimization analysis. The optimization can be used to guide the design of new rural construction in the area and the energy saving transformation of the existing rural houses, which can help to achieve the purpose of energy saving and comfort.

Keywords: rural residence; green building; energy consumption; multidimensional optimization; particle swarm optimization; regression analysis

1. Introduction

Owing to the significant increase in global temperatures, climate change has become more apparent over recent decades [1]. In turn, many countries and governments have taken measures to reduce the adverse effects of climate warming [2]. Globally, construction industries consumes 40% of the the total energy production, produces 30–40% of all solid wastes, and emits 35–40% of CO_2 [3,4]. The green building (GB) has gained substantial support as a solution for minimizing the environmental impacts of buildings to achieve sustainable development [5].

Developing green buildings is an important way to solve the environmental problems of China's construction industry. With the popularization of the green building, the construction industry began to transform from a high resource consumption industry to one with low and environmental impact [6]. China's 12th "Five-Year plan" focused on popularizing the concept of green development, improving energy saving technology standards and realizing the scientific transformation of urban and rural construction mode [7]. The 13th "Five-Year plan" will still have energy-efficient building and green building development as focus point. In addition, according to the regulations that the new urban civil construction meet all the energy conservation standard requirements will, by 2020, have the urban green buildings account for 50% of the new buildings [8]. China's green buildings are all distributed in cities and towns, but at present, China is still a big agricultural country. The rural population accounts for about 43.9% of the total population [9]. A total housing construction area of about 27.8 billion square meters and accounting for about 65% in the rural area of China [10], the energy-saving work of rural buildings is also particularly important. In addition, because the majority of researchers concentrated in universities and the lack of appropriate technical guidance and policy support, the energy-saving technical guidance or standards for China's rural areas are still very scarce. Almost all of China's existing energy-saving standards are aimed at the urban buildings [11]. With the development of economy, people's demand for indoor thermal environment is increasing, correspondingly. The proportion of building energy consumption is also increasing [12]. So, the rural buildings should also take measures to move closer to green buildings gradually. But at present, the energy saving design and renovation of rural areas is still blindly copying the urban living standards, the construction of rural residential buildings has always been the individual behavior of farmers, who rarely consider the energy-saving design [10]. Within comparison to the developed countries, China's building energy-saving work started late, especially in the small cities and rural areas. This paper based on the investigation of some rural areas, sums up that the rural residential building mainly presents the following characters: only 7% of the farmers take the roof insulation measures, about 60% buildings are without the shading devices, the orientation of the building is cluttered. See Section 2.1 for details.

The energy saving research should combine with the local natural climatic conditions and resource conditions [13]. Building energy efficiency is mainly embodied in two aspects: active energy-saving design and passive energy-saving design. The former exists in the late period of building construction, mainly for improving energy efficiency; which includes the equipment installed, lighting systems, heating ventilating & air conditioning system (HVAC) [14]. The latter exists in the early stage of building's construction and mainly for reducing the building energy demand [15]. Among them, the influence of the building envelope and shape coefficient cannot be ignored [16–20]. Passive design occupies a large proportion in different green building evaluation standards. (As show in Figure 1). The process of green building design requires the project team to constantly hold in mind the building's performance in respect of the energy efficiency, material use, indoor environment quality and so forth. It takes much less resources to have a major impact on these aspects if the initiatives are taken from the earliest design stage. Main passive design parameters can be classified to four categories as mentioned in the introduction: the building layout, envelope thermophysics, building geometry and infiltration, and air-tightness [21–24]. In addition, these strategies can be further refined, as shown in Figure 2. Their variation ranges are determined in compliance with the local building practices and engineering experiences [25–27]. For instance, the maximum possible window U-value is determined by the effective upper limit of the glazing generated by EnergyPlus, while the maximum external obstruction angle (defined as the angle between the horizontal line at the window sill level and the line connected with the highest point of obstruction faced by the building [24–26]) is derived by assuming a typical building height of 100 m and a minimum road width of 5 m according to the Building Ordinance in Hong Kong [28]. Different studies use different energy consumption evaluation indicators. Most of the heat load, cold load, or annual air conditioning load [29–31]. Additionally, there are some typical indicators such as EC, peak design load, and load distribution [32,33].

For solving the EC, the simulation software is simple and easy to operate, which provides the research foundation for the passive energy-saving optimization design. The reliability of these simulation tools has been tested and proved by various studies [34–43]. For example, a study developed by Yaşa [44] analyzed the effects of 7 different courtyard shapes on indoor thermal comfort and EC, as well as the influence of solar absorption on building surface under different courtyard shapes and solar movement on buildings thermal performance in the hot-wet, hot-dry and cold climate zone by using the CFD software (ANSYS, USA). N Sadafi et al. [9] tested the influence of the courtyard on the thermal performance of the bungalow in tropical climate zone, by using the Ecotect software (Square One, Britain).

The existing research on residence shows that a large number of scholars have conducted a series of targeted and in-depth studies on the existing residential buildings in different climatic zones from different perspectives, but only a few involve the rural residential buildings in the HWWZ. Moreover, most studies have only analyzed the impact of a single factor on EC. A study developed by Seyedehzahra Mirrahimi et al. [19] has shown that a strong relationship exists between various building components such as shading devices, external wall, roof and external glazing' insulation and reducying EC. Based on the example of typical rural houses in Quanzhou City, Fujian, China, this study aims to comprehensively analyze the quantitative relationship between passive design parameters (which include building shape coefficient, thermal performance parameters of enclosure structure, shading measures, and natural ventilation) and EC. It help to achieve energy saving and comfort, and can be used to guide the construction of new countryside and the energy saving reform of the existing rural buildings.

This paper is divided into 5 sections. Section 2 describes the methodology used in the simulations, the result of field investigation and the different influencing factors. The results are presented in Section 3, followed by the discussion in Section 4. The conclusions are presented in Section 5.

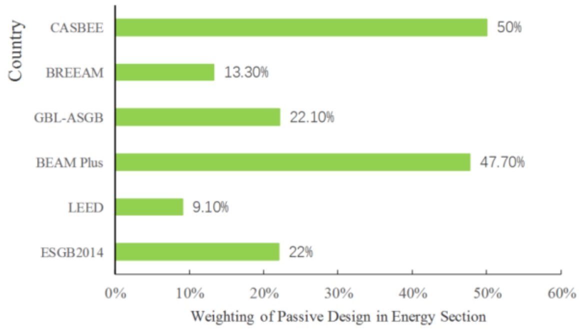


Figure 1. Passive design weighting in energy section.

(This drawing comes from the author's hand drawing referring to the green construction standards).

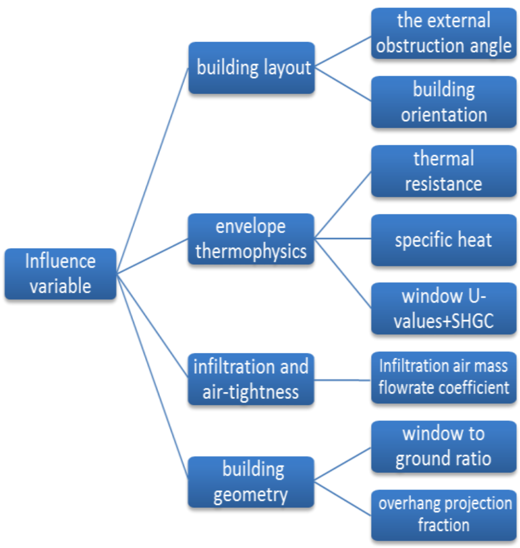


Figure 2. Passive design variable.

2. Research Methodology

2.1. Field Investigation

Through field investigation, we can know the characteristics of the typical rural housing and the current situation of the energy use, to provide the basis for the study. Therefore, the author investigates 30 rural households, located in three villages in Quanzhou City, Fujian, China.

Because of the limit of economic level and bad weather such as typhoon, coupled with the lack of professional guidance, supervision and management of relevant departments, there are many places to be improved in the building construction.

The main features of the local farmhouses are the following:

(1) Most of buildings are built along the street. 66% of the building's direction is roughly south and north, the rest for the east and west.
(2) The thermal insulation of building envelope is poor. Most of the walls are made of 240 mm thick solid clay brick, which has large heat transfer coefficient (K). Most of the houses with rigid cement flat roofs that lack the necessary insulation that leads the top floor's temperature to be much higher. A majority of the external windows (Ew) are single layer glass window with poor shading.
(3) Ew are rarely configured with the necessary external shading components. The vast majority of shade forms are curtains. Accordingly, solar heat gain is great.
(4) The survey on thermal comfort are shown in Figure 3. Nearly 90% of occupants feel hot in summer; More than half occupants feel more comfortable in the transition season, while nearly 30% occupants feel hot; nearly half occupants in winter feel more comfortable, and nearly 30% cold.
(5) Most of the houses here are equipped with courtyard to enhance natural ventilation.
(6) Electric is the main form, in which cooling energy consumption account for the largest. Appliance usage is shown in Table 1. Cooling equipment mainly consists of air conditioners and fans.
(7) The energy using in the region was electricity, natural gas and coal, among them, electricity consumption approximately accounted for 90.9%. According to the market statistics, the electricity cost distribution of the non-air conditioning season is shown in Figure 4. The average electricity consumption in the air conditioning season is 2–3 times that of the non-air conditioning season. Although the energy used high, but the thermal comfort is relatively poor. How to reduce energy consumption under ensuring indoor thermal comfort is the focus.

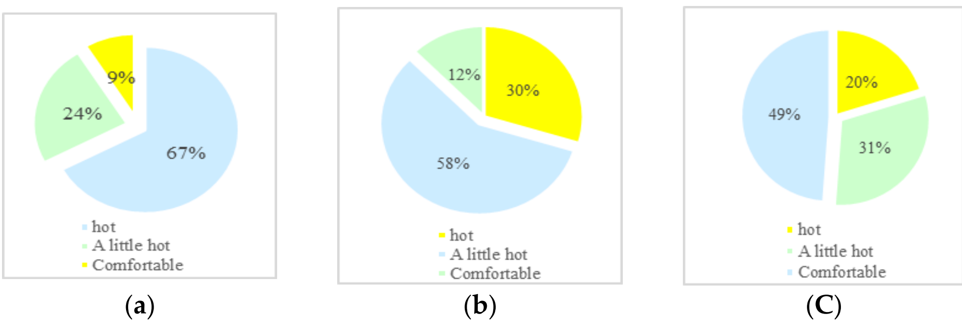


Figure 3. Thermal comfort research. (**a**) Summer; (**b**) Transition season; (**c**) Winter.

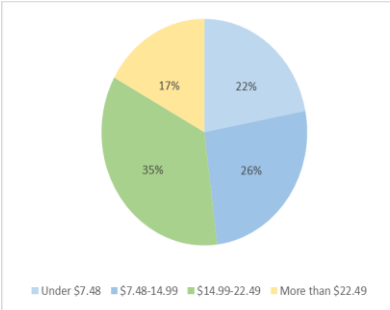


Figure 4. Cost distribution map of non-air conditioning season electricity.

Table 1. The average use of household electrical appliances.

Domestic Appliance	Computer	Air Conditioner	Fan	TV	Washing Machine
Numbers/household	0.70	1.52	2.78	1.57	0.61
domestic appliance	Refrigerator	electromagnetic oven	electric cooker	electric water heater	
Numbers/household	1.43	1.30	1.17	1.00	

2.2. Simulation Model

According to the above research results, with the improvement of the economic level, one-storey residence in rural areas has been gradually eliminated, and the two-storey residence (TB) and the three-storey residence (THB) gradually increased. Therefore, the study is based on these two building types. The layout and dimensions of TB and THB has the same layout and size. Their basic information is: the total height is 7.8 m and 11.7 m; the building area is 331.8 m^2 and 497.7 m^2; the air conditioning area is 136.08 m^2 and 204.13 m^2, respectively. The volumetric 3D model and the floor plan can be observed in Figure 5. The building was modeled by EnergyPlus software (Department of Energy and Lawrence Berkeley National Laboratory, USA), version 8.1.

Based on the principle of unsteady heat transfer, the dynamic load of the building is calculated by the response coefficient method. This method takes into account the attenuation and the delay effect of the enclosure structure with the outdoor temperature. Therefore, it can accurately simulate the dynamic load and energy consumption of the building. The core of EnergyPlus is the calculation area of air heat balance equation. The specific form is as follows [45]:

$$\sum_{i=1}^{N} q_{i,c}A_i + Q_{other} + G_a c_p (T_{a-out} - T_{in}) + Q_{heat-extra} = pVC_p \frac{dT_{in}}{dt} \tag{1}$$

$q_{i,c}$—Convective heat transfer, W/m^2;
N—Surface number of retaining structures;
A_i—The actual heat transfer area on the envelope surface, m^2;
Q_{other}—The latent heat Caused by solar radiation, equipment, lighting and personnel heat convection section and water evaporation, W;
$Q_{heat\text{-}extra}$—the heat need to be discharged, W;
G_a—The sum of the fresh air and the wind, kg;
C_p—Air specific heat capacity at constant pressure, W/(kg·K);
$T_{a\text{-}out}$—Outdoor air temperature, K;

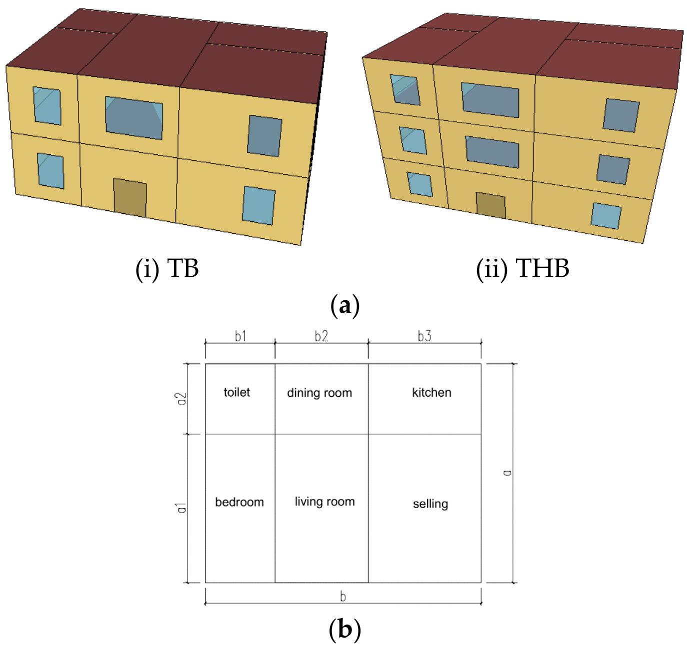


Figure 5. Building model and floor plan. (**a**) Volumetric model in 3D; (**b**) Floor plan.

2.2.1. Meteorological Data

The SWWZ, located in southern China, is a new focus of energy conservation work in China. The region has a population of about 150 million and a relatively high standard of living, with GDP accounting for 17.4% of the country. According to the monthly average temperature in January (11.5 °C), the zone is divided into two sub regions. The buildings in the north area not only need to consider the summer air conditioning, but also need to consider winter heating. The buildings in the southern district only need to consider the summer air conditioning. Quanzhou is located in the southeast coast of Fujian Province, belonging to the subtropical marine monsoon climate, and the type of building thermal partition in this area is hot summer and warm winter. Due to the lack of meteorological data in the typical meteorological year in Quanzhou, use the meteorological data of the Xiamen area similar to Quanzhou in climate instead. Information on the TRY (Test Reference Year) weather data for the city of Xiamen is given in Figure 6.

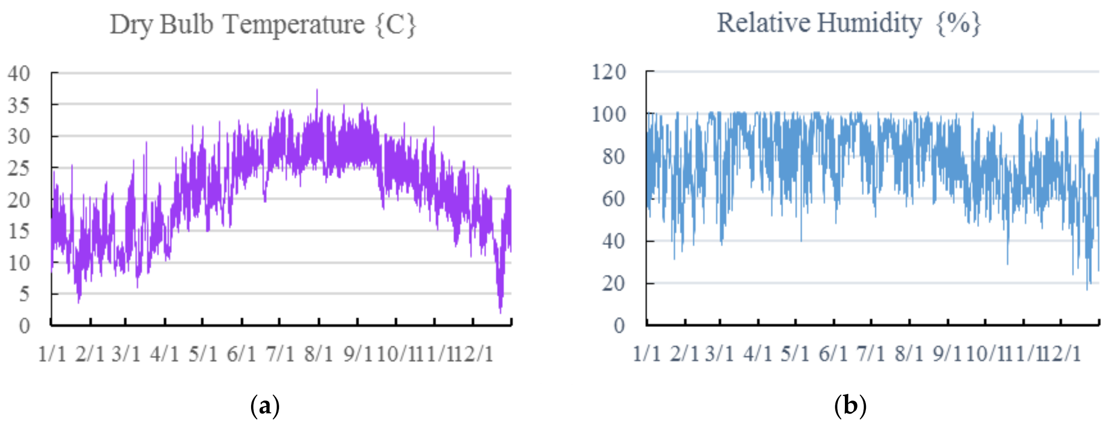


Figure 6. *Cont.*

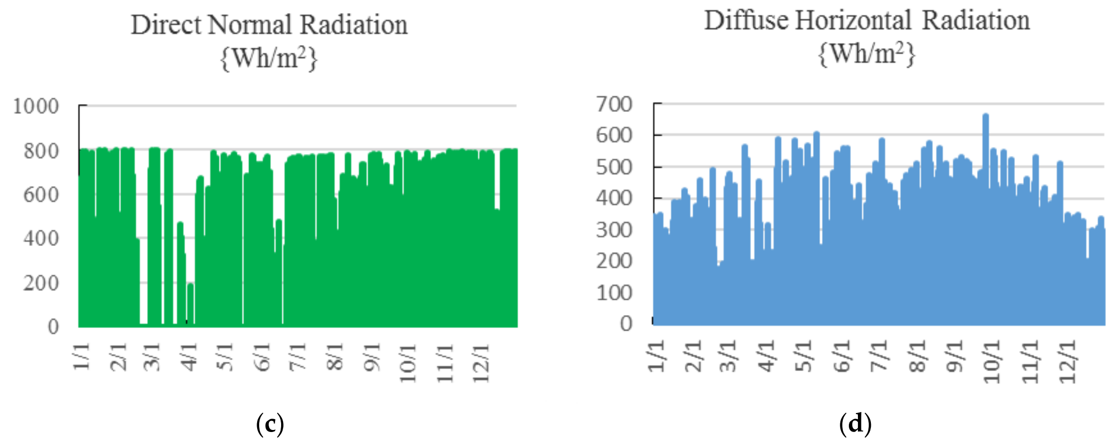


Figure 6. Weather data. (**a**) Dry bulb temperature; (**b**) Relative humidity; (**c**) Direct normal radiation; (**d**) Diffuse horizontal radiation.

2.2.2. Parameters of Retaining Structure

According to the design standard of "Fujian residential building energy efficiency design standard" [46], combined with the local resource conditions, the initial parameters of the model envelope are shown in Table 2.

Table 2. Parameters of retaining structure.

Name	Structure	TT/m	K/W/(m^2·K)
EW	CM (20 mm) ACHB (190 mm) CM (20 mm)	0.230	1.655
Roof	MRT (30 mm) FAC (40 mm) EPS (30 mm) RC (110 mm) BP (25 mm) EPB (35 mm) CM (20 mm)	0.240	0.695
Ew	AW	-	2.822

2.2.3. Occupation, Equipment and Lighting System

Table 3 presents the internal loads related to occupation, equipment, and lighting system. All the values assumed are based on the China Regulation for Residential Buildings [47] and the survey results. According to local farmers' living habits and local development, personnel occupancy and light utilization are shown in Figure 7. Through the research results, the local people generally only use natural daylight during the day. In addition, the automatic control system is relatively backward in this area. Therefore, the use of lighting system has only two modes 0 and 1 (Where 0 represents the whole off, 1 represents the full open). The Utilization ratio are same for weekdays and weekends. The metabolic rates were determined based on the activity performance in each environment. The values for the metabolic rates were based on the ASHRAE Standard 55 [48]. Considering an average skin area of 1.80 m^2, the metabolic rates were defined as follows: for each bedroom 81 W; for the living room 108 W; and for the kitchen 171 W. When more than one person occupies the kitchen, the metabolic rate for one will be set at 171 W while for the other people it will be set at 108 W.

Table 3. Data of Occupation, equipment and lighting system.

Name	Selling	Toilet	Bed Room	Living Room	kitchen	Story
People (p)	8	2	2	4	2	1
Lights (W/m^2)	6	2	3	4	4	2
Electric Equipment (W)	170	0	80	70	350	0

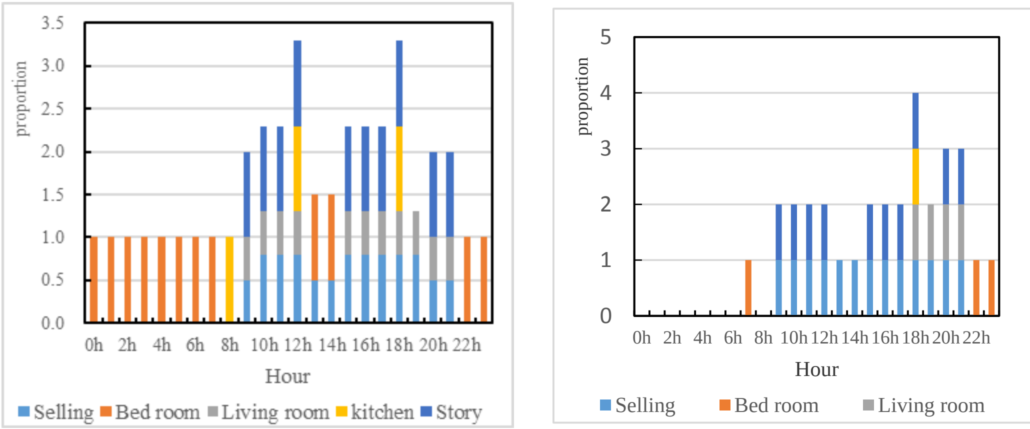


Figure 7. Utilization ratio. (**a**) Occupation; (**b**) lighting system.

2.2.4. Air Conditioning System Setting

According to the standard [46,49], the energy-saving design of residential buildings in the HSWW only considers summer air conditioning. In accordance with the needs of inhabitants, room function and energy use habits, the canteen and the bedroom are set to the refrigeration room.

Split air conditioners are the most commonly type used in Chinese rural. In this study, air conditioners were modeled as a Packaged Terminal Heat Pump (PTHP) system. According to the standard [50], the cooling thermostat were set to 26 °C. The coefficient of performance (COP) is 3.0 W/W for cooling according to the standard. The air infiltration rate of air conditioning room is 1 times/h. Ventilation frequency of room without air conditioning facilities was 5 times/h. Air conditioning schedule is presented in Table 4. Combined with the local climate conditions, the cooling time is set for each year from 15 May to 15 October.

Table 4. Air conditioning schedule.

Room Name	Cooling Time
Canteen	9:00–21:00
Bedroom	12:00–14:00; 20:00–24:00

2.3. Particle Swarm Optimization Algorithm

The PSO algorithm, proposed by Dr. Kennedy and Dr. Eberhart [51,52], is a kind of evolutionary algorithm. It starts from a random solution and then finds the optimal solution using an iterative method, at last evaluates the quality of solution using fitness. The algorithm can solve the optimization problem of the independent variable as a continuous variable, a discrete variable or both continuous variables and discrete variables. It has the advantages of easy realization, fast convergence and high precision. The PSO originated from the study of bird prey behavior, simulating the foraging behavior of birds. Suppose there is only one piece of food in the search area, and no birds know the exact location of the food, but they can search for the current position from the food. The PSO algorithm takes advantage of such "bionics" principle, gets inspiration from this model, and is used to solve the optimization problem in practical engineering. Particle swarm algorithm in detail, see the literature [51,52].

Assuming that the population has a particle number of N, the Q dimension (that is the dimension of each particle) is searched. Each particle is represented as $X_i = (X_{i1}, X_{i2}, X_{i3} \ldots X_{iQ})$, and the velocity corresponding to each particle can be expressed as $V_i = (V_{i1}, V_{i2}, V_{i3} \ldots V_{iQ})$. In addition, each particle has to consider two factors in its search:

1. Search for the best historical values $P_{i;}$

$$P_i = (P_{i1}, P_{i2} \ldots P_{iQ}),\ i = 1, 2, 3 \ldots N \tag{2}$$

2. The best values that all particles search for, P_G, $P_G = (P_{G1}, P_{G2} \ldots P_{GQ})$, note that there is only one PG here.

The position and velocity update formula of particle swarm algorithm is given below:

$$v_i^{k+1} = \omega v_i^k + c_1 \times rand() \times (pbest - x_i^k) + c_2 \times rand() \times (gbest - x_i^k) \tag{3}$$

$$x_i^{k+1} = x_i^k + a v_i^{k+1} \tag{4}$$

The "ω" is the coefficient that maintains the original speed, so it is called the inertia weight. The "c_1" is the weight coefficient of particle tracking its own historical best value. It represents the particle's own knowledge, so it is called "cognition". Normally, it is set to 2. The "c_2" is the weight coefficient of the particle swarm optimum, which represents the particle's knowledge of the whole population, so it is called social knowledge, which is often called "society". It is usually set to 2. The "Rank ()"is a uniformly distributed random number within the [0, 1] interval. The "a" is a factor added to the velocity at the time of updating the position. This factor is called the constraint factor and it is usually set to 1.

2.4. EnergyPlus and GenOpt Coupling

The GenOpt optimization software is coupled with the Energy Plus simulation software to reduce the workload of simulation. With this type of research variables (both discrete variables and continuous variables) and application scope of optimization algorithm, this research use PSO in the GenOpt software to optimize the factors affecting the EC. The logical relationship between the GenOpt software and the EnergyPlus software is shown in Figure 8.

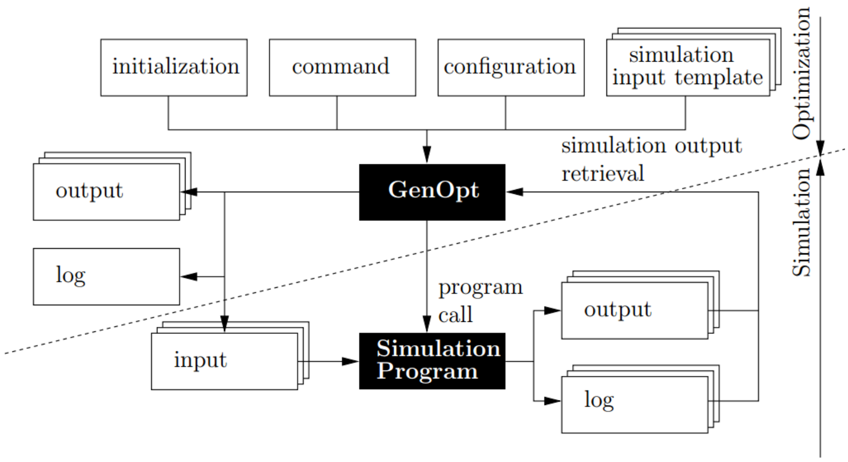


Figure 8. Interface between GenOpt and the simulation program that evaluates the cost function [53].

2.5. Passive Design

2.5.1. Shape Parameter

In the initial stage of building design, building shape parameters including the length, the width and length-width ratio (LWR) need to be considered. In fact, the area occupied by rural housing is often fixed, so the paper only analyses the LWR when the building area is constant.

The window area directly affects the solar radiation heat gain, which is the main factor affecting cooling load in HSWW. LWR and WFR are set as variables. The range of parameters and the optimal steps size are shown in Table 5.

Table 5. Parameter setting of length-width ratio and window—area ratio.

Variable	Initial Value	Minimum Value	Maximum Value	Step	Algorithm
LWR	1.5	0.3	3.0	0.1	Parametric Runs
WFR (TB)	0.253	0.103	0.404	0.030	Parametric Runs
WFR (THB)	0.265	0.104	0.426	0.032	Parametric Runs

2.5.2. Envelope Parameters

In Quanzhou, residential buildings pay attention to insulation, shading and ventilation, and most of them show the architectural features of lightweight, transparent, the architecture pattern of external seal and internal open.

1. Thermal characteristics of exterior walls and roofs

The type and thickness of the insulating material will affect the heat transfer coefficient (K). The widely used insulation materials and their main properties in Fujian province are shown in Table 6. The thickness range, the dispersion and the optimal step size are shown in Table 7.

Table 6. Main physical properties of thermal insulation materials.

Type	IM	Density	K	S
		(kg/m^3)	(W/(m·K))	(J/(kg·K))
EW	EPS	24	0.035	1210
	EP	16	0.052	1260
	GIM	64	0.046	960
	ACHB	650–750	0.53	–
Roof	EPB	29	0.029	1210
	EP	16	0.052	1260
	EPS	24	0.035	1210
	EPB	29	0.029	1210

Table 7. Thickness range and difference of thermal insulation material.

Name	IM	Thickness Range (m)	Dispersion (m)	Step
EW	PB	0–0.06	0.005	12
	EP	0–0.06	0.005	12
	ACHB	0–0.24	0.02	12
	GIM	0–0.06	0.005	12
roof	——	0–0.15	0.01	14

2. Thermal characteristics of external windows

The heat gain from the Ew accounts for 40–50% of it from the enclosure. There are two main parameters to evaluate the thermal performance of the Ew: K, ($W/m^2{\cdot}K$) and the solar heat gain coefficient (SHGC). In the thermal design standard of building envelope [54], the focus of the Ew is the K while in the north area and the SHGC while in the south area. Keep the parameters of the EW and roofs in Table 1. There are 11 types of Ew were selected. The SHGC of No. 1–5 is similar, but the K is different; for the No. 5–9, the K is the same but the SHGC is different; No. 10 is the most widely used form of Ew; No. 11 is a new energy-saving windows more respected at present in the hot summer and warm winter climate zone. Table 8 presents the main parameters of the different types of Ew.

Table 8. Main parameters of different types of external windows.

Number	Form	K(W/(m·K))	SHGC
1	Glass (3 mm) Air (6 mm) Glass (3 mm clear)	3.172	0.762
2	Glass (3 mm) Air (12 mm) Glass (3 mm clear)	2.741	0.763
3	Glass (3 mm) Air (15 mm) Glass (3 mm clear)	2.725	0.764
4	Glass (3 mm) Air (16 mm) Glass (3 mm clear)	2.717	0.764
5	Glass (3 mm) Air (9 mm) Glass (3 mm clear)	2.883	0.763
6	Glass (3 mm) Air (9 mm) Glass (3 mm grey)	2.883	0.572
7	Glass (3 mm) Air (9 mm) Glass (3 mm green)	2.883	0.565
8	Glass (3 mm) Air (9 mm) Glass (3 mm bronze)	2.883	0.582
9	Glass (3 mm) Air (9 mm) Glass (3 mm low iron)	2.883	0.828
10	Single layer glass window (6 mm clear glass)	5.778	0.819
11	Single layer glass window (6 mm Low-E glass)	3.437	0.637

Note: clear represents colorless transparent ordinary glass, grey represents the grey endothermic coating glass, green represents the green glass coating absorbs heat, bronze represents the bronze endothermic coating glass, and low iron represents the low iron glass.

2.5.3. External Shading System

From the practical and economic aspects, external shading system is more likely to be used in residential buildings, especially in the rural areas. The use of external shading measures can improve the WFR, which meets the design trend of large windows in the zone.

The variables that affect the EC are the overhangs length (OL) in different directions, the distance between the sun visor and the window (H), and the extended length of the sun visor (EL). The default overhangs' length is 0.6 m. In order to simplify calculation, it is assumed that the EL and the Ew is same. The reasonable ranges of different variables, the dispersion and the optimal step size are shown in Table 9. When studying the horizontal sun shading board (HSSB), the EL_v is fixed to 0.20 m; the OL_v is divided into 0.2 m, 0.6 m, 1.0 m, 1.4 m and 1.8 m. When studying the vertical sun shading board (VSSB), the H_h is fixed to 0.10 m, the OL_h is divided into 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m.

Table 9. Parameter setting in different shading forms.

Variables	Form	Variable Range (m)	Dispersion (m)	Step
OL	HSSB	0–1.8	0.2	9
	VSSB	0–1.0	0.1	10
H	HSSB	0–0.5	0.1	5
	VSSB	0–0.3	0.05	6
EL	HSSB	0–0.5	0.05	10
	VSSB	0–0.5	0.05	10

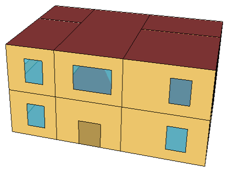
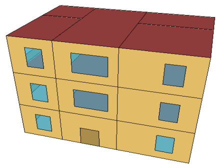
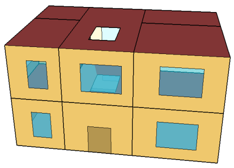
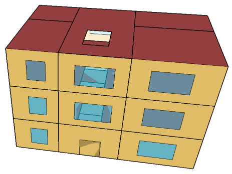
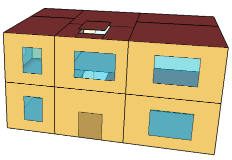
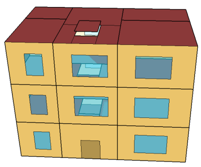
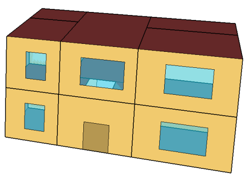
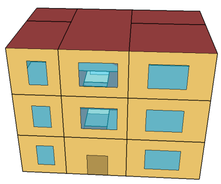
2.5.4. Natural Ventilation

Affected by the monsoon climate, the ventilation potential of Quanzhou is superior. However, there are still 30% of the summer weather static wind. So, hot ventilation play a supplementary role in residential ventilation. Therefore, the rural residential buildings pay more attention to the organization of hot pressing ventilation in architectural design. "Courtyard buildings" came into being. Combining field survey and CFD simulation, Wajishani Gamage provides evidence for the potential of cross ventilation of intermediate spaces through the air-well in the Chinse Shophouse [55]. This paper studies the effect of different courtyard conditions on EC and indoor environment. Table 10 shows the four conditions' set and Table 11 shows the corresponding model.

Table 10. Setting the working condition of courtyard.

Working Condition	Courtyard	Open State
1	No	Top closure
2	Yes	Open top
3	Yes	Top half closed
4	Yes	Top closure

Table 11. The volumetric 3D model under different working conditions (Courtyard size: 2 m × 3 m).

Working Condition	TB	THB
1		
2		
3		
4		

Note: for "open courtyard" condition, the wall of the living room in top floor, which connected to the courtyard, is considered EW. The first and the middle floor is considered inner wall.

3. Results

3.1. Single-Objective Optimization

3.1.1. Building Shape Parameter

It can be seen from Figure 9 that with an increase of the LWR, the EC decreases firstly and then increases gradually. For TB and THB, EC reach the smallest when LWR is 0.9 and 1, respectively. When the LWR changes, the EC changes 0.05 kWh/m^2 and 0.20 kWh/m^2 for TB and THB, respectively, which may be related to the building function and building volume. Therefore, it not have a big effect in reducing EC by setting the LWR of the rural housing.

As can be seen from Figure 10, the EC is proportional to the WFR. The growth trend of EC of the TB and the THB all are linear.

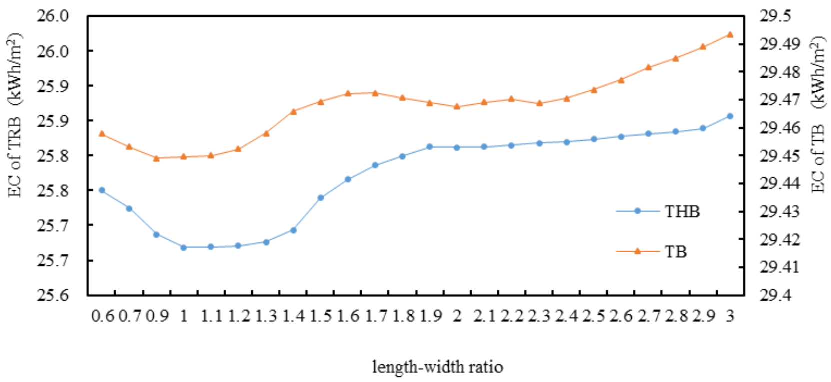


Figure 9. Relationship between length-width ratio and energy consumption.

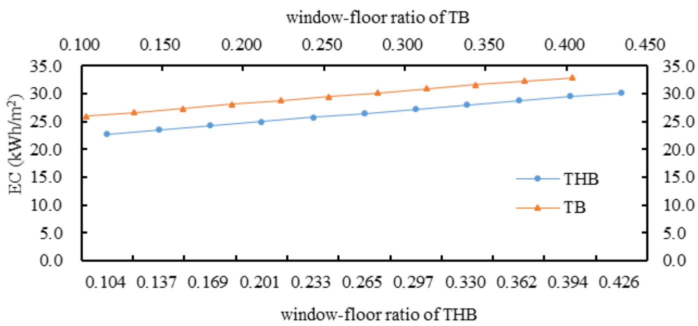


Figure 10. Relationship between window-floor ratio and energy consumption.

SPSS20.0 is a statistical software used to analyses the correlation. Table 12 shows that the EC and the LWR have a significant positive correlation at the 0.01 level; The Pearson correlation coefficient of the THR is larger than that of the TR, the LWR of THR has a greater impact on EC. The regression analysis between the WFR and the EC are shown in Table 13. The linear fitting degree of the two curves is very good, and the difference is significant.

Table 12. Correlation between energy consumption and length-width ratio.

EC (kWh/m^2)		r
TB	Pearson correlation	0.623 **
	Significant (bilateral)	0.001
TRB	Pearson correlation	0.775 **
	Significant (bilateral)	0.000

Notes: ** Significant correlation at 0.01 level (bilateral).

Table 13. Fitting relationship between window-floor ratio and energy consumption.

Building Type	Regression Equation	Regression Coefficient (R^2)	Significance Test (sig.)
TB	Y = 23.150X + 23.608	1.000	0.000
THB	Y = 23.400X + 20.296	1.000	0.000

3.1.2. Envelope Parameters

1. Heat insulating material

The relationship between the thickness of insulation material and EC is hyperbolic, and the trend is gradually slowing down, as shown in Figure 11. The insulation performance from good to bad is followed by the Polystyrene board (EPS), the glass beads of inorganic dry powder insulation mortar (DIM), the expanded perlite (EP), but little difference. When the insulation thickness is less than 120 mm, the insulation performance of ceramsite concrete hollow block (CCHB), which belong to the self-insulation structure, is worse than the three kinds mentioned. When the thickness is more than 120 mm, the heat insulation effect is significantly increased. According to the heat insulation effect in three kinds of roofing insulation materials, extruded polystyrene board (EPB) is best, followed by the EPS, the worst is the EP.

The average indoor temperature of the living room on the top floor without the need for cooling was simulated to reveal the influence of different thermal insulation materials, as shown in Figure 12. In order to guarantee the comparison of simulation results, the thickness of thermal insulation layer of EW was set to 30 mm (Due to the special nature of self-insulation structure, the thickness of CCHB is 110 mm.), and the thickness of thermal insulation material of the roof is set to 60 mm.

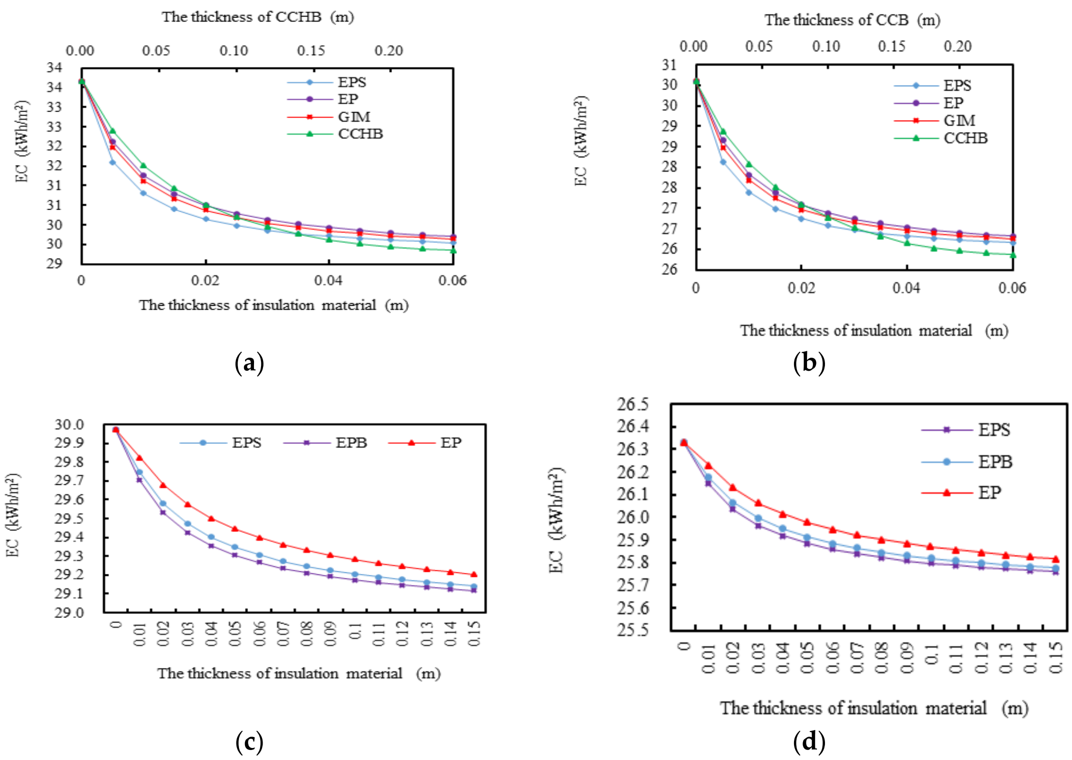


Figure 11. Relationship between thermal insulation material and energy consumption. (**a**) Two-storey residence (exterior wall); (**b**) Three-storey residence (exterior wall); (**c**) Two-storey residence (roof); (**d**) Three-storey residence (roof).

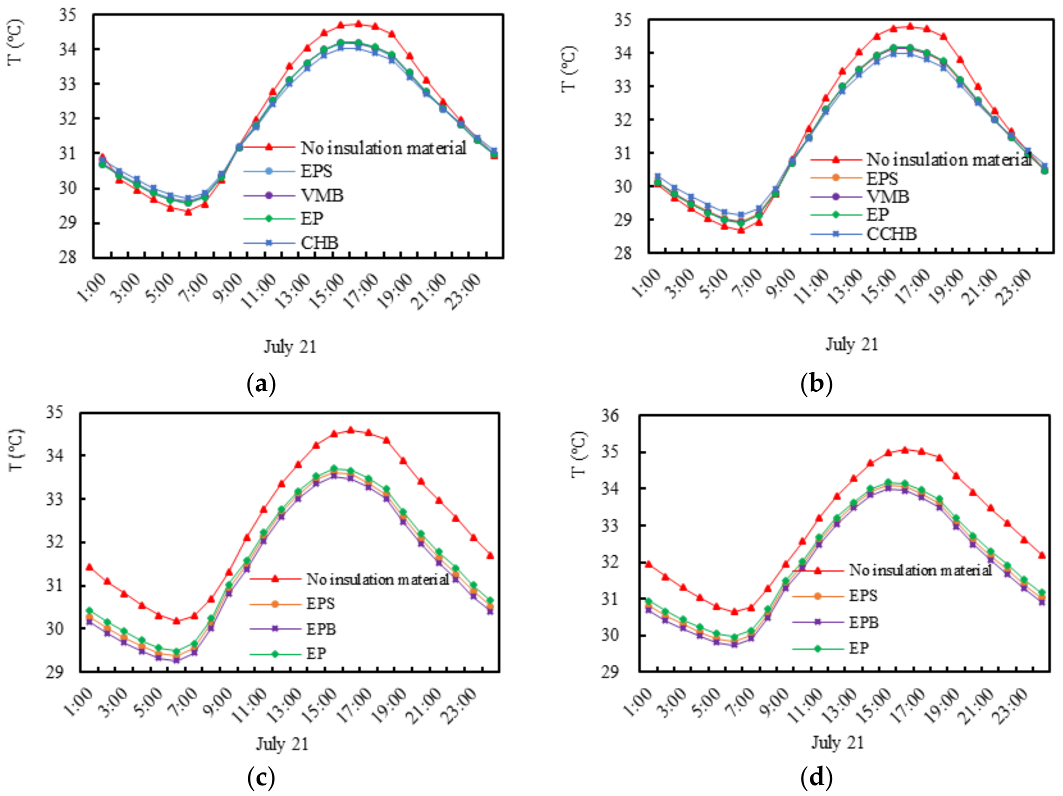


Figure 12. Temperature variation of living room under different insulation materials. (**a**) Two-storey residence (exterior wall); (**b**) Three-storey residence (exterior wall); (**c**) Two-storey residence (roof); (**d**) Three-storey residence (roof).

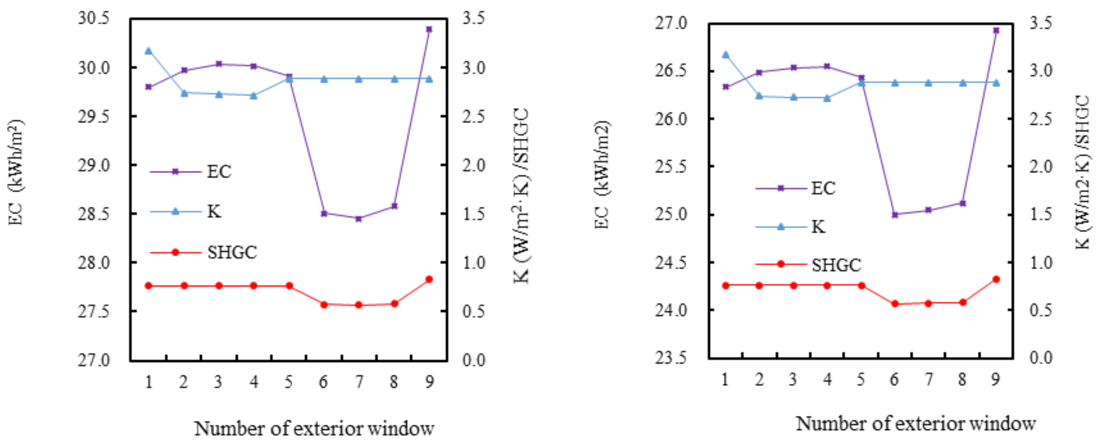
Figure 12a,b show that: the influence of EW's insulation measures on the indoor average temperature is not too large, and the effect of both four kinds of materials is very small. In addition, the EW's insulation can effectively reduce the temperature during the day; however, it is not conducive to the external heat dissipation at night.

Figure 12c,d show that: roof insulation has a more obvious effect on reducing the indoor average temperature, and the effect of three kinds of materials is similar. Because of the delayed effect, the temperature reduction reaches the peak value at 19:00. Combined with room properties and the local habits, this moment is the intensive time for the room staff activities. Therefore, roof insulation can improve the thermal comfort of the top floor room.

2. Thermal performance of exterior window

The correlation between the EC and the Ew's K and SHGC can be observed in Figure 13. When the SHGC remained the same, EC increases with the decreasing of K; when the K is consistent, EC decreases with SHGC. In addition, when the TR using the No. 7 form (Green coated hollow heat absorbing glass with thickness of 3 mm) and the THR using the No. 6 form (Gray coated hollow heat absorbing glass with thickness of 3 mm), their EC reached the lowest level.

Correlation analysis is shown in Table 14. There is no significant correlation between the EC and the K of Ew in the two types of buildings. However, there is a significant positive correlation between the SHGC and the EC at the 0.01 level. This result is consistent with the local standards of Fujian province [56]. The influence of the K of Ew can be ignored, compared to the SHGC.



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

Figure 13. Relationship between thermal performance of exterior windows and energy consumption. (**a**) Two-storey residence; (**b**) Three-storey residence. Note: SHGC of the working condition 1–5 is the same, the K of the working condition 5–9 is the same, and the working conditions 10 and 11 are not drawn into the picture.

Table 14. Correlation between energy consumption and thermal performance of exterior windows.

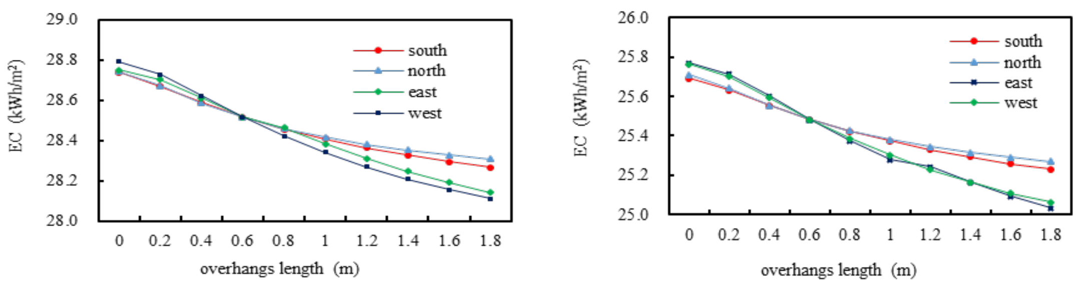
Building Types		K (W/m^2·K)	SHGC
TB	Pearson correlation	0.155	0.969 **
	Significant (bilateral)	0.650	0.000
THB	Pearson correlation	0.172	0.968 **
	Significant (bilateral)	0.612	0.000

Note: ** At the 0.01 level (bilateral) significant correlation.

3.1.3. External Shading System

1. The overhangs length of sun visor

The influence of the OL on the EC are presented in Figure 14. As can be seen from Figure 14a,b, horizontal visor decreases the EC significantly. With the increasing of OL in different directions, the EC decreases faster in west and east than in south and north. As can be seen from the Figure 14c,d, the Ew is more suitable for the vertical visor in south and north, especially in the south; Energy-saving effect is slightly worse by setting the vertical visor in the east and west. Comparison of Figure 14a,d found that the energy-saving effect of both the horizontal visor and the vertical visor in the northern is not significant.



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

Figure 14. *Cont.*

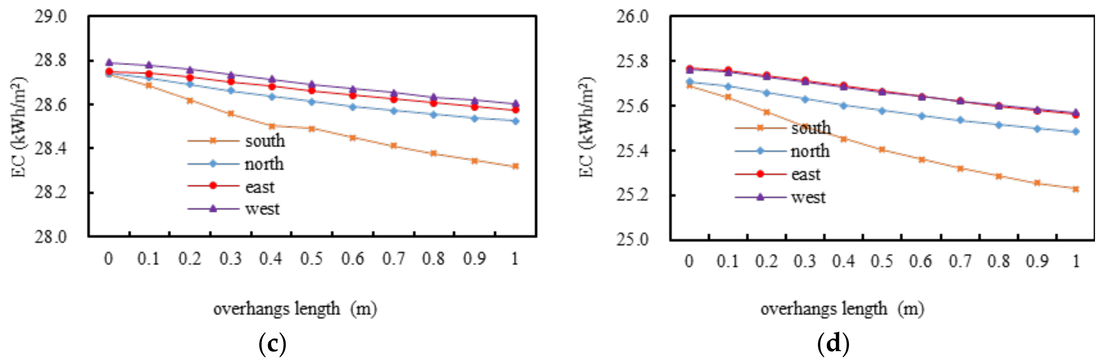


Figure 14. The relationship between energy consumption and the overhangs length of visor. (**a**) Two-storey residence (Horizontal visor); (**b**) Three-storey residence (Horizontal visor); (**c**) Two-storey residence (Vertical visor); (**d**) Three-storey residence (Vertical visor).

2. Distance between sun visor and window

Figure 15a,b show the relationship between the EC and the H_h. With the H_h increasing from 0 to 0.5 m, the EC increases gradually. The growth rate in south and west is the fastest. In addition, in north and east, the effect is relatively small. In east, when the H_h increases to 0.4 m, EC reduction is very small. In general, from the energy point of view, the smaller the distance, the more energy-efficiency under the premise of the conditions allow. Energy saving effect of vertical shading is very poor in the east to the west; therefore, this section analyzes the influence of H_v and Ew in the south and north on the EC, as show in Figure 15c,d. The EC with an increase in the H_h in south and north. If the Ew with a vertical visor in north and south, under the conditions permit, the distance between vertical visor and Ew should be chosen as small as possible.

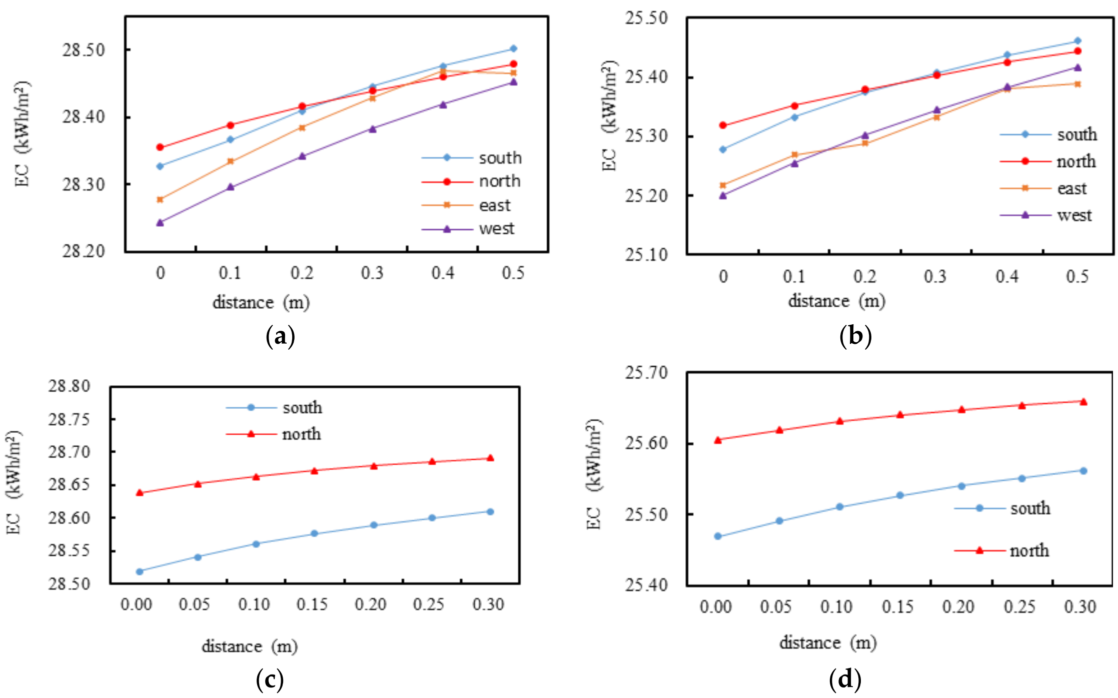


Figure 15. Relationship between energy consumption and the distance from the windows to visor. (**a**) Two-storey residence (Horizontal visor); (**b**) Three-storey residence (Horizontal visor); (**c**) Two-storey residence (Vertical visor); (**d**) Three-storey residence (Vertical visor).

3. Extension length of sun visor

Figure 16a,b show the relationship between the EC and the EL_h. Both the EL_h (increases from 0 to 0.5 m) and the OL_h (varies among 0.2 m, 0.6 m, 1.0 m, 1.4 m, and 1.8 m) affect the energy saving performance. When OL_h is 0.2 m, increasing EL_h has little energy-saving effect; with the increasing of OL_h, energy-saving effect of EL_h is more obvious. Therefore, when the OL_h reaches a certain value, it is possible to reduce the solar heat gain by increasing the EL_h; and when smaller EL_h, the energy-saving effect is not ideal.

Figure 16c,d show the relationship between EC and EL_v. When EL_v increases from 0 to 0.5 m, if OL_v is different (0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1.0 m), the energy saving effect are also different and the amplitude is small. Energy-saving effect of the EL_v increases with the increase of the OL_v. However, compared with the horizontal visor, the energy-saving effect of EL_v is very small.

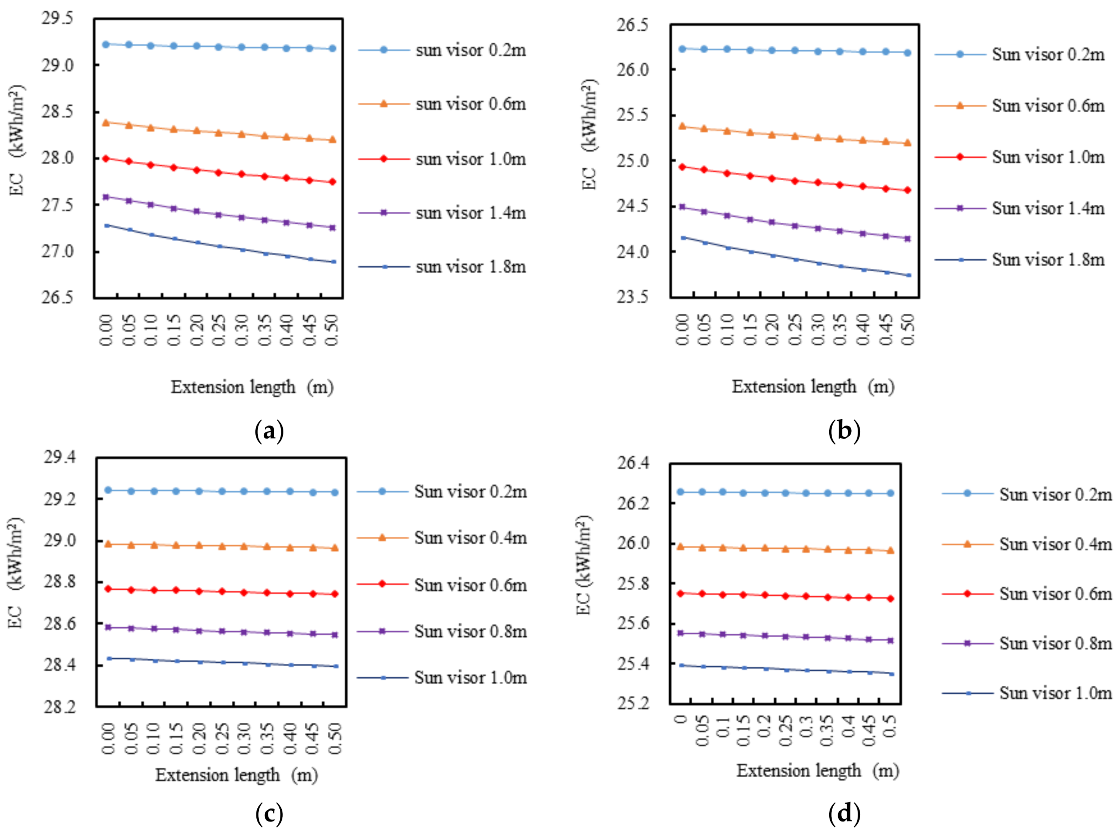


Figure 16. The relationship between the extension length of sun visor and energy consumption. (**a**) Two-storey residence (Horizontal visor); (**b**) Three-storey residence (Horizontal visor); (**c**) Two-storey residence (Vertical visor); (**d**) Three-storey residence (Vertical visor).

3.1.4. Natural Ventilation

1. Influence of natural vitiation on energy consumption

Annual energy consumption is shown in Figure 17. There is little difference under four conditions. The main reason is that household air conditioning equipment is only installed in the bedroom, but not in the area (living room, kitchen, and dining room) connected with the outside. Additionally, compared with the relatively closed space, the design of the courtyard has a greater impact on the connected space on EC.

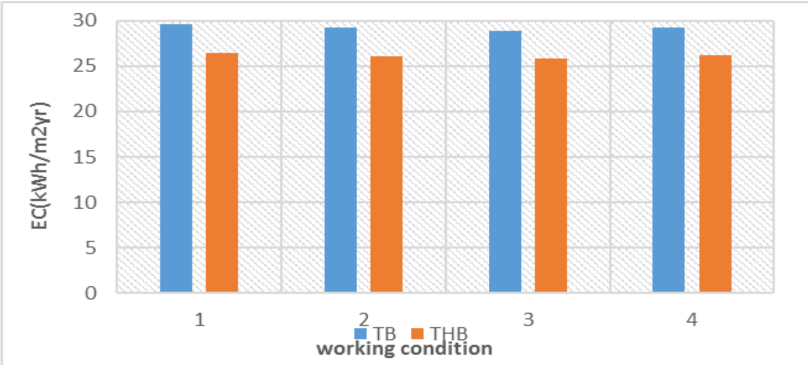


Figure 17. Comparison of EC under different working conditions of courtyard.

2. Influence of a courtyard on an indoor environment

Previous studies show that the courtyard enhances ventilation of residential buildings in hot climate regions, which can effectively improve the indoor thermal environment [57,58]. The indoor temperature change of the top floor and the first floor living room under different working conditions is shown in Figures 18–20.

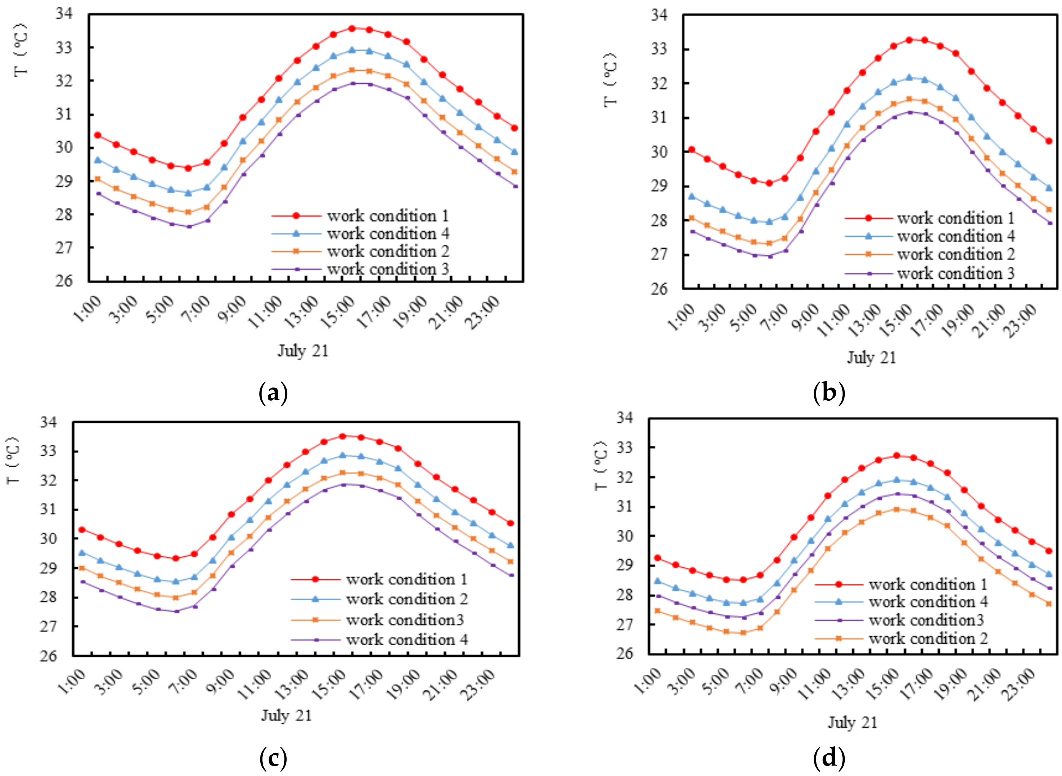


Figure 18. Hourly average indoor temperature in transition summer; (**a**) The living room on the top floor of TB; (**b**) The living room on the first floor of TB; (**c**) The living room on the top floor of THB; (**d**) The living room on the first floor of THB.

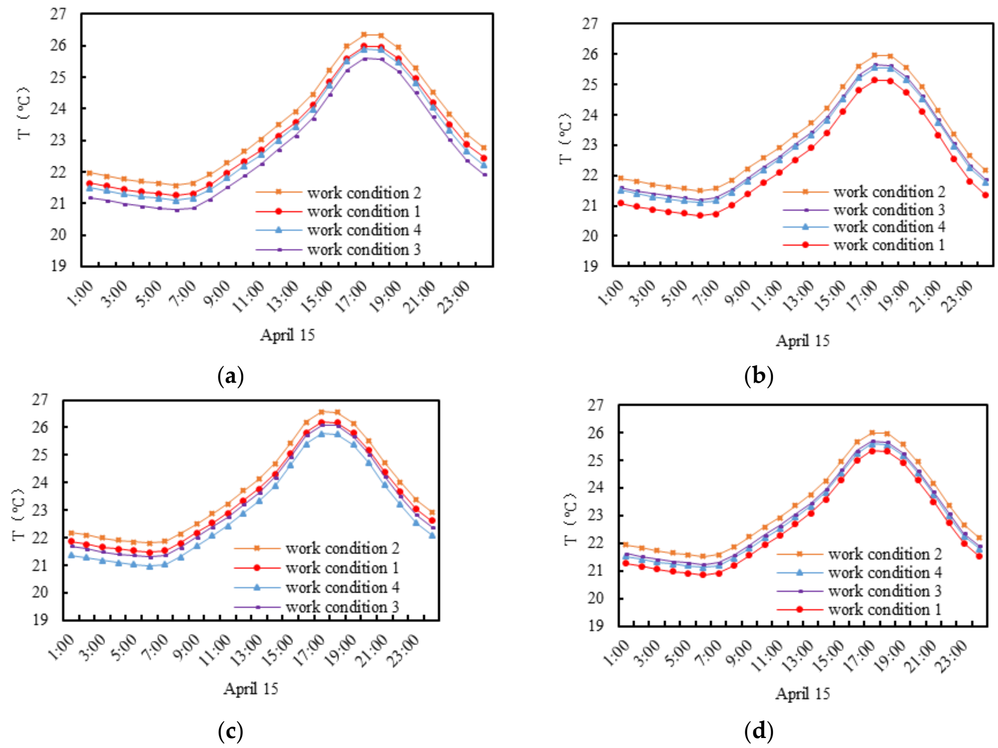


Figure 19. Hourly average indoor temperature in transition season. (**a**) The living room on the top floor of TB; (**b**) The living room on the first floor of TB; (**c**) The living room on the top floor of THB; (**d**) The living room on the first floor of THB.

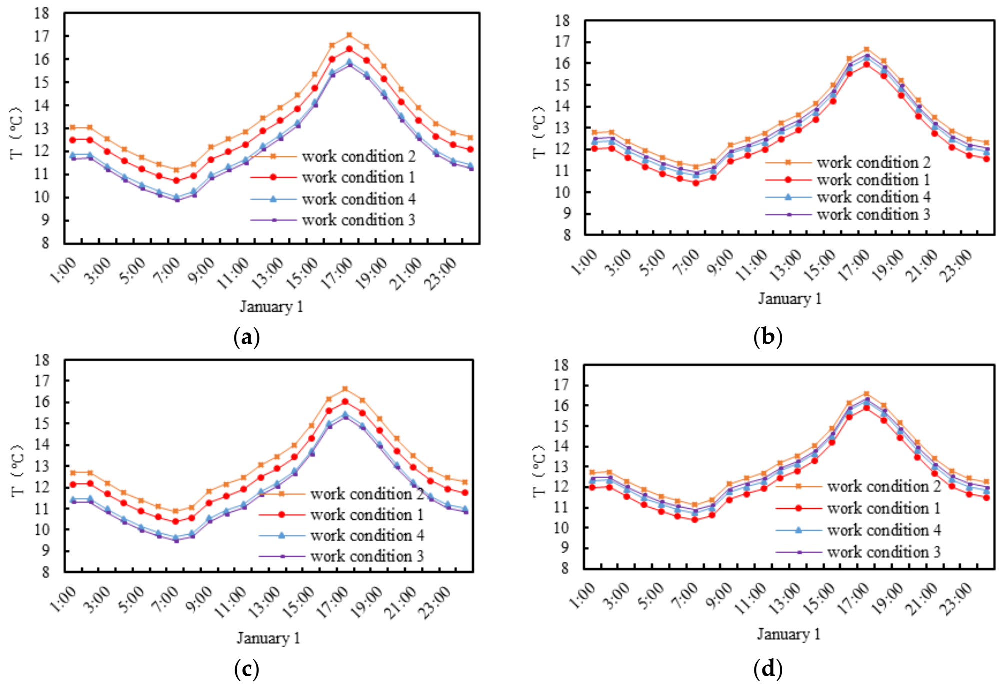


Figure 20. Hourly average indoor temperature in winter. (**a**) The living room on the top floor of TB; (**b**) The living room on the first floor of TB; (**c**) The living room on the top floor of THB; (**d**) The living room on the first floor of THB.

Combined with Figure 18a,b, for both TB and THB, a courtyard can effectively reduce the indoor temperature in summer. The maximum temperature that can be reduced is by about 1.81 °C. The indoor temperature under different working conditions is as follows: condition 3 < condition 2 < condition 4. The main reason is that although the open state can enhance natural ventilation, the strong direct solar radiation makes the top living room receive more heat in the summer. Moreover, the closed state is not conducive to airflow. Therefore, it is best to reduce the temperature in a semi-open condition. Compared with Figure 18a,b, courtyard's influence on the first floor's living room is more obvious than the top floor's living room. The comparison of Figure 18a,d shows that the first floor living room's indoor temperature is the lowest compared to other conditions when the courtyard of TB and THB are under semi-open and open states, respectively. The main reason is that the effect of solar radiation on the first floor of the living room is reduced with the increase in floor height. For THR, the air circulation effect is better in a fully open state than in a half-closed state.

Compared with summer, courtyards have no obvious effect on the indoor temperature in the transitional season and winter, as shown in Figures 19 and 20. Setting up courtyards can raise the indoor temperature of the first floor living room. Its influence on the top floor is related to the work condition. The indoor temperature in four conditions is TB: condition 2 > condition 1 ≈ condtion 4 > condition 3; THB: condition 2 > condition 1 ≈ condition 3 > condition 4. The average temperature of the top living room is the same under four conditions.

The ASHRAE Standard 55 adaptive model of the 90% acceptability is selected to assess the indoor operative temperature under naturally ventilated conditions for hot and humid climates according to previous research conducted by the authors. The 90% acceptability limits of the operative temperature are defined by Equations (5) and (6) [48].

$$T_{o,up90} = 0.31T_{ao} + 20.3 \tag{5}$$

$$T_{o,low90} = 0.31T_{ao} + 15.3 \tag{6}$$

where $T_{o,up90}$ is the upper limit of acceptable operative temperature; $T_{o,low90}$ is the lower limit of acceptable operative temperature; and T_{ao} is the prevailing mean outdoor air temperature.

Under the adaptive model, the indoor comfort conditions of a typical day under different natural ventilation conditions are shown in Table 15. For the THB, four working conditions can only be able to fully meet the ventilation comfort conditions in the transition season typical daily, but the winter and summer meet rate is low. Ventilation and air conditioning can be used to maintain indoor thermal comfort. For the TB, four working conditions cannot meet the comfort conditions in three typical design days. From the thermal comfort conditions, the THB is more appropriate. In addition, the working condition 2 is more favorable.

Table 15. Adaptive model evaluation results.

Building Type	Floor	Working Condition	In 1 January	In 15 April	In 21 July
TB	Top	1	0.0%	58.3%	0.0%
		2	0.0%	62.5%	20.8%
		3	0.0%	50.0%	33.3%
		4	0.0%	54.2%	0.0%
	First	1	37.5%	58.3%	0.0%
		2	62.5%	62.5%	45.8%
		3	54.2%	50.0%	54.2%
		4	54.2%	54.2%	29.2%
THB	Top	1	0.0%	100.0%	0.0%
		2	0.0%	100.0%	0.0%
		3	0.0%	100.0%	0.0%
		4	0.0%	100.0%	0.0%
	First	1	0.0%	100.0%	4.2%
		2	0.0%	100.0%	4.2%
		3	0.0%	100.0%	4.2%
		4	0.0%	100.0%	4.2%

3.2. Multidimensional Optimization

The influence factors may affect each other, so the univariate analysis may be one-sided. Therefore, it is necessary to simultaneously consider all kinds of factors. Therefore, considering the simulation results of Sections 3.1.3 and 3.1.4, the east and west external windows are configured with horizontal shades, and the north and south external windows are configured with vertical shades. The open courtyard model is chosen as research foundation.

The range of optimization variable, initial value and variable type are shown in Table 16. The parameter setting is shown in Table 17. Multi-optimization results are shown in Table 18. When the building type is TB, EC of the optimized farmhouse is 8.2% lower than that of the existing farmhouse. When the building type is THB, it is about 10.4%. This shows that the optimization of design parameters can significantly reduce energy consumption.

Table 16. Setting optimization variables.

Parameter Name	Value Range	Initial Value	Variable Type	Optimal Step
O	0–180°	0	continuous variable	10
LWR	0.3–3	1.5	continuous variable	0.1
$\mathrm{WAR_{TB}}$	0.103–0.404	0.253	continuous variable	0.03
$\mathrm{WAR_{THB}}$	0.104–0.426	0.265	continuous variable	0.032
EWI	1–4	3	discrete variable	1
$\mathrm{EWIT_{1,2,4}}$ (m)	0–0.06	0.03	continuous variable	0.005
$\mathrm{EWIT_{3}}$ (m)	0–0.24	0.19	continuous variable	0.02
RIM	1–3	3	discrete variable	1
RIT(m)	0–0.15	0.030	continuous variable	0.01
EWT	1–9	8	discrete variable	1
$\mathrm{OL_h}$	0–1.8	0.8	continuous variable	0.2
$\mathrm{H_h}$	0–0.5	0.1	continuous variable	0.1
$\mathrm{EL_h}$	0–0.5	0	continuous variable	0.05
$\mathrm{OL_v}$	0–1.0	0.5	continuous variable	0.1
$\mathrm{H_V}$	0–0.3	0.1	continuous variable	0.05
$\mathrm{EL_v}$	0–0.5	0	continuous variable	0.05

Note: 1–4 types of external wall thermal insulation materials respectively are the EPS, EP, CCHB, and GIM.

Table 17. Parameter setting of PSO.

Parameter Name	Parameter Value
Domain topology	Von Neumann
Particle number (n_P)	10
Subalgebra (n_G)	10
Cognitive acceleration (c_1)	2.8
Social acceleration (c_2)	1.3
Velocity contraction coefficient (λ)	0.5
Maximum velocity dispersion coefficient ($\nu_{\max}$)	4
Initial iteration weight (w_0)	1.2
Final iteration weight (w_1)	0

Note: the meaning and value of each parameter in the table refer to reference [54].

Table 18. Optimization results of particle swarm optimization.

Parameter Name	TB	THB	TB (Not Optimized)	THB (Not Optimized)
O	SE10°	south	south	south
LWR	0.9	1.0	1.5	1.5
WFR	0.193	0.200	0.253	0.265
IM of EW	3	3	3	3
EWIT (m)	0.24	0.24	0.19	0.19
IM of roof	1	1	3	3
RIT (m)	0.06	0.06	0.03	0.03
EWT	7	7	11	11
OL_h	1.4	1.4	0.8	0.8
H_h	0.1	0.1	0.1	0.1
EL_h	0.5	0.5	0	0
OL_v	0.8	0.8	0.5	0.5
H_V	0.05	0.05	0.1	0.1
EL_v	0	0	0	0
EC (kWh/m^2)	28.24	24.41	30.75	27.23
Iterations	340	340	–	–

Note: the third type of EW insulation material is CCHB; the first and the third types of roof insulation material are EPB and PB, respectively; the seventh and eleventh types of windows refers to green film plated hollow glass windows and the single ordinary glass windows.

3.3. Economic Analysis

The Ew's thermal performance in the optimization model is relatively improved, and the insulation thickness is increased correspondingly. This will inevitably lead to the increase of the initial investment. Therefore, this section will make an economic analysis. The farmhouse-designed accordance with the "Standard for energy efficiency of residential buildings in the hot summer and warm winter zone" [59] is defined as the "standard farmhouse" (SF). In order to simplify the calculation, take the electricity price of $0.082/kWh for the region's electricity price. The annual energy consumption and cost of the three types of farmhouses are shown in Table 19.

According to the investigation of the local building materials market, the price of PB, EPB, CCHB, aluminum alloy single frame single layer glass windows, plastic steel single frame hollow glass window, and plastic steel single frame plating green film hollow glass window are $74.96/m^3, $112.44/m^3, $20.99/m^3, $25.49/m^2, $44.98/m^2 and $74.96/m^2, respectively. The increase in the initial investment of the three farmhouses is shown in Table 20.

The Table 21 shows that considering energy consumption, the energy-saving ratio of the optimized farmhouse (OF) is 26–30% corresponding to the existing farmhouse (EF), and that of the SF is 20–22%. Therefore, the OF's energy-saving effect is better. From the economic point of view, the payback period of the OF is about 20 years corresponding to the EF, and that of SF is about 15 years. Therefore, the economic efficiency of SF is better than OF. Considering energy and economy, when the housing service life is more than 21 years, the OF can achieve economic requirements. When the housing service life is less than 21 years, the SF is better. In order to reduce EC, the country can introduce relevant policies to give farmers some subsidies. Additionally, to promote the development of rural energy conservation work, the initial investment can be controlled and be brought within the acceptable range of the farmers' salaries.

Table 19. Energy consumption and cost of three farmhouses.

Building Type	Annual Energy Consumption (kWh/m^2)		Annual Fee ($)	
	TB	THB	TB	THB
EF	38.57	35.04	410.19	558.92
SF	30.75	27.23	326.99	434.33
OF	28.24	24.41	300.30	389.36

Table 20. Increase in initial investment.

Building Layers	Energy Saving Measures	Increase in Initial Investment ($)	
		SF	OF
TB	EW insulation	1286.06	1704.80
	Roof insulation	373.16	1119.64
	Ew	1637.18	3169.12
	total	3296.40	5993.55
THB	EW insulation	1948.73	2454.87
	Roof insulation	373.16	1119.19
	Ew	1627.18	3169.12
	total	3296.40	5993.55

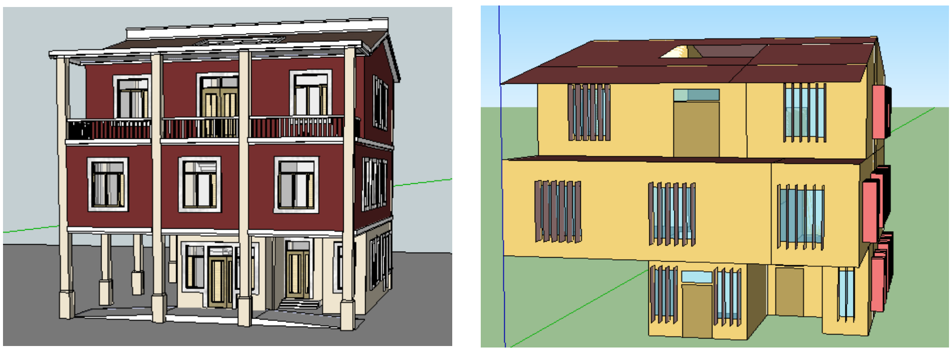
Table 21. Economic comparative analysis.

Building Layers	Contrast Term (A/B)	ECR (%)	Initial Investment Increase ($)	AECR ($)	Payback Period (year)
TB	SF/EF	20.27	3296.40	3213.34	15.4
	OF/EF	26.78	5993.55	281.86	21.3
THB	SF/EF	22.29	4719.04	319.49	14.7
	OF/EF	30.34	8498.65	434.93	19.5

Note: ECR = (the EC of B—the EC of A)/the EC of B; AECR = the AEC of B—the AEC of A; Investment payback period = initial investment increase/AECR.

3.4. Modelling Verification

In order to verify the accuracy of the simulation method, a case study will be performed. The selected model is a typical rural house in the Quanzhou area. The stereoscopic model and the simulation model of the building are shown in Figure 21.



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

Figure 21. Building model. (**a**) Stereo model; (**b**) simulation model.

According to the survey, combined with the local timber companies' information, the installation of the enclosure structure is shown in Table 22.

Table 22. Parameter setting of enclosure structure.

Name	Structure	Aggregate Thickness (m)	K (W/(m^2·K))
EW	CM (20 mm) + SCB (240 mm) + CM (20 mm)	0.28	1.892
roof	roofing tile + Fine stone concrete (40 mm) + RC (110 mm)	0.15	1.830
floor	CM (20 mm) + RC (100 mm) + CM (20 mm)	0.14	3.703
Ew	Single glazing aluminum alloy window	–	5.778

Note: The meteorological data of this model is the same as that of the Section 2.2.1; occupation, equipment, and lighting is the same as that of the Section 2.2.3. The air-conditioning system setting is the same as that of the Section 2.2.4.

According to the survey, the average electricity fee is about $37.48–44.98 in summer and $14.99–22.49 in other seasons. In this study, the summer electricity charge is set at $41.23, and other seasons electricity charge are set at $18.74. In order to simplify the calculation, the price of electricity in this area is set at $0.082/kWh (the average price), and the power consumption in summer is about 274 kWh each month, compared with other seasons. The air-conditioning energy consumption is about 502 kWh/month, and the total consumption is 2510 kWh in the air-conditioning season (15 May–15 October). Additionally, the total electricity consumption in the non-refrigeration season is 1596 kWh. According to the above results, the annual total electricity consumption is about 4106 kWh.

It is worth mentioning that the object in the study is the operating house with a canteen, so the EC of air-conditioning is definitely larger than the ordinary farmers' consumption. Therefore, using the local average energy consumption level to verify the model, will lead to lower accuracy rate. According to the sum of the EC of all the operating residential areas in the investigated area, it can be found that the electricity fee in the refrigeration season was about $104.95, and the electricity fee in other seasons was about $44.98. After calculation, the annual total electricity consumption is about 10,214 kWh. By building the simulation model, the annual energy consumption of the building is about 10,584 kWh, which is lower than the actual consumption of 370 kWh. The deviation in the air conditioning season, non-air conditioning seasons are 7.1% and 5.7% respectively. And it is within the acceptable range. Therefore, the model established by this research is feasible.

4. Discussion

According to GBES, the weight of energy utilization accounts for 24% and 28% for residential buildings and public buildings, respectively. The weight of energy and atmosphere assessment is about 30% in LEED-NC4.0. Therefore, reducing the building energy consumption is an important part of promoting the development of green buildings. From the angle of economic and social development, it is a great impetus to the sustainable development of an economic environment. According to GBES, passive design occupies a large proportion. Therefore, the effect of passive design parameters on BEC and indoor thermal comfort was investigated through building simulation and Particle swarm optimization.

A reasonable setting of LWR helps reduce EC, but its energy saving potential is small. Additionally, the EC per unit area increases linearly with WFR increase. However, this does not mean that the smaller the WFR, the better. According to the standard provisions [59], in order to ensure the effect of natural ventilation, the open area of the residential window shall not be less than 8% of the floor area. Therefore, when determining the value of WFR, the necessary indoor ventilation should be ensured.

The insulation thickness and the EC are hyperbolic. The effect of different insulation materials is less different. The heat insulation of EW has little influence on the indoor average temperature. However, the roof's thermal insulation material can not only reduce theEC, but also improve the indoor comfort. There is no significant correlation between EC and K of Ew, but it has a significant positive correlation with SHGC at 0.01 level. This result aligns with the local standards [23] on not specifying the K of external windows of residential buildings, which are south of HSWW.

Horizontal shading has a significant effect on reducing EC. East and west window can set the horizontal shading device with long overhangs; the south and north windows are more suitable for vertical shading, especially the south Ew. The greater the distance between the sun visor and the outer window, the greater the EC.

Rural residential building generally only install air conditioning equipment in the bedroom, study and other closed areas. Moreover, intermediate spaces next to the air-wells had significantly lower air temperature and heat index [55], the courtyard has a relatively small impact on the closed space, so the impact of courtyards on building energy consumption is not significant. Nevertheless, it can improve the indoor thermal environment of the open space. Its impact on the first floor is significantly greater than its effect on the top floor. Compared with summer, it has less of an influence in the transition season and winter. Combined with the climate characteristics in different seasons of courtyards, it is recommended to add courtyards to improve the indoor thermal environment of the open space and set the open condition of the courtyards according to the outdoor climatic conditions.

An energy-saving optimization analysis for rural residential areas in HSWW was established, which had a practical significance on the design decision-making for such typology of houses. At present, China's energy-saving design and project design are often out of touch, which means that architects often rely on experience and related energy-saving standards or energy-saving design standards. In contrast with the previous results, it can be seen that the optimization results of this study can help designers deal with multidisciplinary and contrasting objectives in the early design stage. It can be used to guide the design of new rural constructions in the area and the energy-saving transformation of the existing rural houses, which can help achieve both energy saving and comfort.

Moreover, it is important to mention that the results are obtained from building energy simulation. Building energy simulation helps understand the impact of different strategies on the building's performance. However, the predicted energy consumption may have some deviation from the actual energy consumption. Additionally, in this study, the home air conditioner was chosen as the refrigeration equipment without any energy-saving measures. This paper takes the annual energy consumption as the objective function to carry out the single objective of multi-optimization. The influence of parameter variation on indoor comfort is not considered in the optimization. For the basic parameters of the PSO, this paper mostly used empirical values that are based on the relevant literature.

5. Conclusions

In order to adapt to the development of green building in response to the 13th "Five-Year plan" of China, improving building performance is one of the top priorities. In this paper, the basic information of the existing rural residential buildings in Quanzhou area is obtained by field research. Using the specifications of the climate zone and the local architecture development trend, to expand based on the existing building model, the influence of building-type parameters, the parameters of building envelopes, the shading system, and natural ventilation measures on EC and thermal comfort were studied. Based on the results presented in this paper the following conclusions can be drawn:

1. The EC increases linearly with the increase of LWR, and first decreases and subsequently increases with the increase of WFR.
2. The relationship between EC and the thickness of EW and roof′ insulation material is hyperbolic. The additional insulation layer on the EW has little effect on the indoor temperature of the top floor room. In contrast, roof insulation measure has an obvious impact on indoor temperature. There is a significant positive correlation between the EC of residential buildings and SHGC at the 0.01 level, which is not significantly correlated with K.
3. For the east and the west windows, this is effective by increasing OL_h, reducing H_h and increasing EL_h. For the south windows, increasing OL_v and reducing H_v can reduce EC. The best sunshade measures for the southern windows should be combined with the local farmers living habits.
4. A courtyard has little effect on EC, but it has an obvious effect on improving thermal comfort. In summer, the courtyard can effectively reduce the indoor temperature, and the effect of lowering the indoor temperature is varies with the different states of the courtyard. Compared with the summer conditions, the courtyard has little effect on the indoor temperature in the transition season and winter. Additionally, the courtyard can raise the indoor temperature of the first-floor living room, and its influence on the top-floor living room is related to the state of it.
5. The results of the multi-dimensional optimization show that the optimal value of building orientation, LWR, WFR in the south, insulation thickness of EW, and roof in the south are 0.9–1.0, 0.193–0.200, 0.24 m and 0.06 m, respectively. The results also indicate that the optimal thermal insulation material of Ew, EW, and roof is steel frame plating green film hollow glass window, CCHB, and eEPB, respectively. For both east windows and west windows, horizontal shading is

optimal. The optimal value of OL_h, H_h and EL_h is 1.4 m, 0.1 m and 0.5 m, respectively. For north windows, vertical shading is optimal; the optimal value of OL_h, H_h and EL_h is 0.8 m, 0.05 m and 0 m, respectively.

6. The optimization results of this study can help designers deal with multidisciplinary and contrasting objectives in the early design stage. It can be used to guide the construction of new countryside and the energy saving reform of the existing rural buildings. It is beneficial to the construction of sustainable buildings.

Acknowledgments: This research has been supported by 'National Key R&D Program of China' (Grant No. 2016YFC0700100).

Author Contributions: Shilei Lu conceived the research and designed the research methods; Ran Wang analyzed the data, wrote and improved the paper; Shaoqun Zheng performed the simulation.

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

Abbreviations

The following abbreviations are used in this manuscript:

EC	Energy consumption (kWh/m^2)
HWWZ	hot summer and warm winter zone
TB	Two-storey residence
THB	Three-storey residence
SF	Standard farmhouse
EF	Existing farmhouse
OF	Optimization farmhouse
EW	Exterior wall
Ew	Exterior window
K	Heat transfer coefficient ($W/m^2{\cdot}K$)
CM	Cement mortar
ACHB	Aggregate concrete hollow block
CCHB	Cceramsite concrete hollow block
MRT	Metal roofing tile
FAC	Fine aggregate concrete
EPS	Polystyrene board
RC	Reinforced concrete
BP	Bottom plate plastering
AW	Aluminum alloy single frame hollow glass window
EPB	Extruded polystyrene board
EP	Expanded perlite
GIM	Glazed hollow bead inorganic dry powder insulation mortar
VMB	Glass beads
CHB	Concrete hollow block
SCB	Solid clay brick
S	Specific heat
WFR	Window-floor ratio
LWR	length-width ratio
SHGC	solar heat gain coefficient
HSSB	Horizontal sun shading board
VSSB	Vertical sun shading board
O	Building orientation
IM	Insulation material
RIT	Roof insulation thickness (m)

RIM	Types of roofing insulation materials
EWIT	External wall insulation thickness (m)
EWT	Exterior window type
EWI	Types of external wall insulation
OLh	Overhangs length of the horizontal shading
OLv	Overhangs length of the vertical shading
ELh	Extension length of horizontal shading
ELv	Extension length of the vertical shading
Hh	Distance between horizontal visor and window
HV	Distance between vertical visor and window

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