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Parametric Study on Residential Passive House Building in Different Chinese Climate Zones

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Abstract: With the increasing of building energy consumptions, the related issues of energy crisis and environmental pollution become more and more prominent. As an effective energy-saving technology, the passive house (PH) has been widely applied in China to reduce the building energy utilization. However, the design and application of PH vary with different climate conditions. Therefore, it is significant to conduct the parameterization of PH and propose a suitable design zoning of PH in China. In our study, a comprehensive feasibility analysis of the implementation of PH is performed, which chooses 31 representative cities covering 5 climatic regions. The sensitivity analysis firstly filters the key parameters that heavily affect energy consumption. The results indicate that the key parameters include external wall heat transfer coefficient (WU), basement ceiling heat transfer coefficient (BCU), solar heat gain coefficient (SHGC), glass G value (UG), heat recovery efficiency (HERE) and humidity recovery efficiency (HURE). Then, with the multiple regression approach, the values of key parameters are optimized. Based on the determined values of sensitive parameters, the design zoning of PH in China is finally proposed, which can guide the design of PH as well as enhance the application of PH in China.

Keywords: passive house; sensitivity analysis; design parameter optimization; design zoning

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1. Introduction

The global energy consumption is mainly concentrated in building, transportation and industry, of which the building field accounts for 40% [1,2]. In China, building energy consumption accounts for 28% of domestic energy consumption. However, with the rapid growing of building areas and the improvement of people's life quality, this proportion will increase to 40% by 2030, and notably the residential sector will account for 62% of total building energy consumption [3]. To alleviate energy demand, the concept of low energy buildings has been proposed, e.g., zero energy building, green building, PH [4]. The Ministry of Housing and Urban-Rural Development of the People's Republic of China also put forward the technical standard for nearly zero energy buildings to reduce the energy consumption of residential buildings by more than 60% [5].

As a typical type of low-energy building, the concept of PH was proposed by Dr. Feist of the Passive House Institute (PHI) aiming to provide a comfortable indoor environment with minimum energy demand [6]. A PH should obey five principles: (i) High level of thermal insulation; (ii) minimization of thermal bridges; (iii) high-efficiency windows; (iv) airtightness; and (v) mechanical ventilation with heat recovery system [7]. Compared with traditional buildings, PH can save up to 90% of heating energy and 50% of cooling and dehumidification energy [8]. To obtain the PH certification, the building must meet the passive house standard (PHS): Annual heating or cooling demand must be equal or less than 15 kwh/m^2, the primary energy use must be equal or less than 120 kwh/(m^2 a) and the tightness level (n50) must be equal or less than 0.6 h^{-1} [9]. As an effective technique of building energy conservation, PH has achieved unprecedented development in China. As estimated, by 2020, there will be 5000 new PHs in China with a total building area of 100 million square meters [10].

In order to investigate the energy-saving performance of PH, extensive research had been carried out. Through energy consumption monitoring, Dan et al. [11] found that the primary energy demand of residential PHs was less than 120 kwh/(m^2 a). Mahdavi et al. [12] found that PH apartments consume approximately 65% less heating energy and 35% less electrical energy than low-energy apartments. The life cycle results show that the built residence with PHS provides a reduction of cumulative energy demand of 24–38% compared with the conventional building standard TEK 10 [13]. Besides, in comparison with traditional retrofit schemes, renovation methods based on PHS have higher energy efficiency [14,15]. Therefore, PHs have great energy conservation potential both to new construction and existed buildings. For PH, the Passive House Planning Package (PHPP) is used as a common building energy-benchmark system to forecast heating demand [16], cooling demand [17] and primary energy demand [18]. It considers a larger range of internal heat gains in buildings, such as heat recovery [19]. PHPP is more precise than similar design tools, calculating the energy balances of a building to an accuracy of ± 0.5 kWh. [20] However, the core technical indicators of PH are determined with the climatic conditions of Central Europe, so the application in other climate areas must address climate adaptation issues. Jürgen et al. [21] have proved that all relevant climate zones in the world can realize PHs by using damp thermodynamic simulations. Badescu [22,23] used the PHPP to prove that Romania and parts of the southern hemisphere can meet the PHS. However, in warmer climates, the PHS cannot be met [24,25]. To achieve PHs in all climate zones, design parameter optimization has become the key to solving the climate adaptation problem [26]. Currently, parametric optimization focuses on design parameters of envelope structure and air tightness [27,28]. For example, Ferrante [29] and Tommerup [30] conclude that the key to meet PHS is to optimize the insulation layer thickness of the envelope. Badescu et al. [31] found that the overheat rate and the cooling load can be reduced by adjusting the night ventilation in summer. Parker et al. [32] pointed out that the residence can meet the PHS after optimizing the thermal performance and air tightness and other technical parameters. Parametric optimization analysis showed that SHGC and window wall ratio are the sensitive parameters in hot and humid climates [33]. Georges et al. [34] found that the PH can meet the heating demand of 10 W/m^2 when the air exchange frequency is 0.3–0.4 h^{-1} by sensitivity analysis. Research on PH mostly focused on cold regions and less on warm regions. Therefore, the energy efficiency index and design parameters in other climates are often ignored, such as refrigeration energy consumption and refrigeration dehumidification efficiency.

To solve the climate adaption issues of PH in China, this research studies the feasibility of PH in Chinese various climate zones; determines the key design parameters affecting energy consumption; and obtains the appropriate values and ranges of key design parameters. PHPP is applied to simulate the heating, cooling and primary energy consumption of $2000 - \times 31 - \times 2$ cases in 31 cities and analyzes the difficulty of realizing the PHS in China's climate regions. The parametric optimization considers 13 design parameters affecting energy consumption, and the standard regression coefficient (SRC) method is used to determine the key design parameters. The values and ranges of sensitive parameters are obtained based on multiple regression analysis, and the design zoning of residential PH in China is proposed.

2. Methodology

2.1. Simulation Models

2.1.1. Climate and Locations

To verify the rationality of parametric research on PH in China, this paper selects 31 representative cities. These 31 cities cover five thermal climate zones: Severe cold (SC), cold (C), hot summer and cold winter (HSCW), hot summer and warm winter (HSWW), and M (warm). Meanwhile, the meteorological data of 31 cities can be obtained from the official institutions for static PHPP simulation. Table 1 shows the geographic information of 31 cities, as well as the heating degree days (HDD) and cooling degree days (CDD) [35,36].

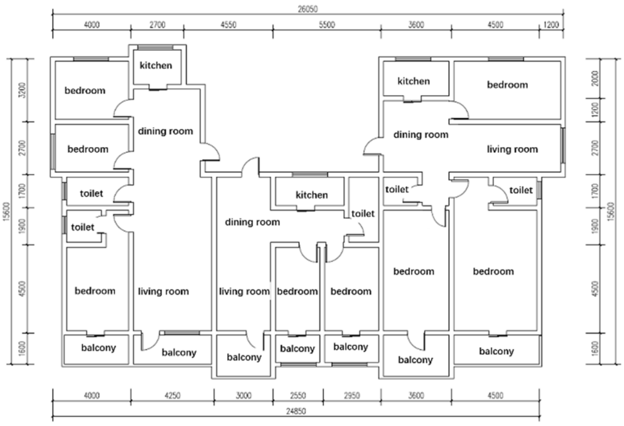
Table 1. Main information on research site.

No.	Climate Zone by China	City	Longitude, Latitude	Altitude (m)	CDD Base 26 °C	HDD Base 18 °C
1	SC	Harbin	126.63° E, 45.75° N	142	8	5418
2	SC	Changchun	125.30° E, 43.92° N	237	5	4944
3	SC	Shenyang	123.38° E, 41.80° N	45	15	4007
4	SC	Hohhot	111.63° E, 40.80° N	1063	2	4528
5	SC	Xining	101.82° E, 36.62° N	2295	0	4441
6	SC	Urumqi	87.60° E, 43.77° N	935	33	4531
7	C	Lhasa	91.03° E, 29.65° N	3649	0	3553
8	C	Beijing	116.47° E, 39.90° N	31	71	2795
9	C	Tianjin	117.17° E, 39.17° N	3	57	2738
10	C	Shijiazhuang	114.43° E, 38.05° N	81	85	2558
11	C	Jinan	117.03° E, 36.67° N	170	136	2252
12	C	Zhengzhou	113.70° E, 34.73° N	110	114	2197
13	C	Xi'an	108.92° E, 34.25° N	398	111	2349
14	C	Taiyuan	112.55° E, 37.85° N	778	4	3115
15	C	Lanzhou	103.83° E, 36.05° N	1517	2	3231
16	C	Yinchuan	106.22° E, 38.47° N	1111	1	3556
17	HSCW	Shanghai	121.43° E, 31.20° N	6	136	1586
18	HSCW	Nanjing	118.77° E, 32.05° N	7	187	1936
19	HSCW	Hefei	117.27° E, 31.85° N	27	176	1836
20	HSCW	Hangzhou	120.17° E, 30.25° N	42	175	1555
21	HSCW	Nanchang	115.88° E, 28.68° N	47	259	1425
22	HSCW	Wuhan	114.33° E, 30.62° N	23	273	1632
23	HSCW	Changsha	112.92° E, 28.20° N	68	180	1554
24	HSCW	Chongqing	106.55° E, 29.55° N	259	184	1104
25	HSCW	Chengdu	104.07° E, 30.65° N	506	32	1372
26	HSWW	Fuzhou	119.32° E, 26.03° N	84	262	723
27	HSWW	Guangzhou	113.30° E, 23.17° N	41	283	394
28	HSWW	Haikou	110.17° E, 20.05° N	14	358	63
29	HSWW	Nanning	108.35° E, 22.78° N	122	265	431
30	M	Guiyang	106.72° E, 26.57° N	1224	6	1605
31	M	Kunming	102.70° E, 25.05° N	1892	0	1224

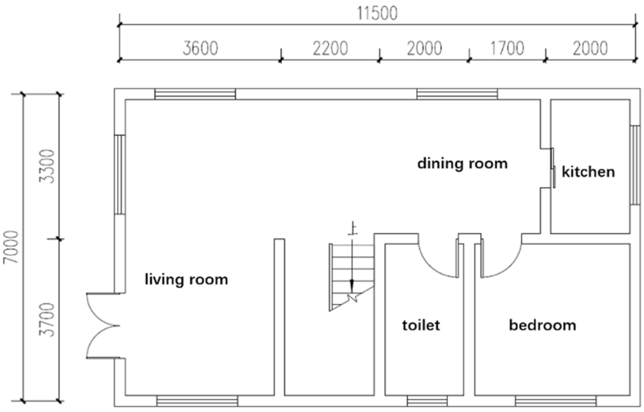
2.1.2. Software and Building Models

The PHPP developed by PHI is a powerful software for calculating and verifying the energy consumption of PHs. The calculation results are the decisive basis to judge whether the buildings can meet the PHS [37]. According to PHI's study, it is found that PHPP can be used in China [38].

Two types of residential building digital models are established in PHPP, namely high-rise and villa buildings, which considers the influence of building shape coefficient on building energy consumption. Model 1 in Figure 1 is based on a representative PH in China, named C15, in the "Waterside" project in Qinhuangdao, Shandong Province. This is an 18-floor high-rise residential building with an underground parking lot. The building presents an air-conditioned area of 352 m^2 on each floor with a height of 3 m. There are three units on each floor. Model 2 in Figure 1 is for a single-family residence with two stories, slab on grade. It has about 150 m^2 of occupied floor area (~75 m^2 per floor); the interior floor plan's dimensions are 7 m × 11.5 m (the long side facing North/South), with 2.8 m ceiling heights and a roof truss with horizontal ceiling insulation. Each model is equipped with a fresh air system with independent control and heat recovery systems for heating and cooling. In addition, using the model to simulate cities located in different climate zones, the PHPP models are slightly modified according to national and local regulations, climatic conditions and regional habits. The details of two models are presented in Table 2.



(**a**) Model 1



(**b**) Model 2

Figure 1. Plan schemes of model 1 and model 2.

Table 2. Parameter setting details of two PHPP models.

	Model 1	**Model 2**
Building area (m^2)	6718	148
Treated floor area (m^2)	5689	156
No. of dwelling units	54	1
No. of occupants	133.1	2.9
External wall U-Value (W/m^2 K)	0.13	0.14
Roof U-Value (W/m^2 K)	0.11	0.11
Basement ceiling U-Value (W/m^2 K)	0.12	0.13
Partition wall U-Value (W/m^2 K)	0.27	0.38
U-Value window frame (W/m^2 K)	0.65	0.59
Absorption coefficient wall	0.8/0.4	0.60
Absorption coefficient roof	0.90	0.90
Window wall ratio (N.E.S.W)	0.15/0.13/0.45/0.09	0.26/0/0.71/0.02
Solar heat gain coefficient	0.50	0.50
U-value glazing (W/m^2 K)	0.58	0.70
Shading (N.E.S.W)	0.43/0.31/0.4/0.32	0.89/1/0.83/0.84
Air tightness (h^{-1})	0.50	0.22
Heat recovery efficiency	80%	83%
Humidity recovery efficiency	Yes	No
Mechanical cooling	Yes	No
Window night ventilation in summer, manual, (h^{-1})	0.36	0.15
Air change rate via the vent. A system with supply air (h^{-1})	0.50	No
Window ventilation air change rate in summer (h^{-1})	0.16	0.36
Internal heat gains (W/m^2)	1.60	2.40

2.1.3. Design Parameter

This paper selects 13 variables: Roof heat transfer coefficient (RU), exterior window frame heat transfer coefficient (UWF), exterior wall absorption coefficient (ACW), roof absorption coefficient (ACR), exterior wall window eave length (WUG), night ventilation efficiency (NVE), AT, BCU, SHGC, WU, UG, HERE and HURE. The selected parameters have great influence on the consumption and thermal comfort of PHs [39,40]. Meanwhile, these parameters are heavily dependent on climate conditions [41,42]. The range of parameters is determined by the Green Building Evaluation Standard and the Passive Ultra Low Energy Green Building Technical Guidelines, as shown in Table 3 [43,44].

Table 3. Details of study design parameters.

No.	Parameter	Range	Unit	Probability Distributions
1	Wall U-Value	0.1~0.3	$W/(m^2 K)$	continuous
2	Roof U-Value	0.1~0.25	$W/(m^2 K)$	continuous
3	Basement ceiling U-Value	0.18~2	$W/(m^2 K)$	continuous
4	U-Value window frame	0.8~1.5	$W/(m^2 K)$	continuous
5	Absorption coefficient wall	0.4~0.95	-	continuous
6	Absorption coefficient roof	0.4~0.95	-	continuous
7	Solar heat gain coefficient	0.1~1	-	continuous
8	U-value glazing	0.1~1.5	$W/(m^2 K)$	continuous
9	Windows overhang shading	0~1	m	continuous
10	Air tightness	0.5~1.0	h^{-1}	continuous
11	Heat recovery efficiency	0~95%	-	continuous
12	Humidity recovery efficiency	0~90%	-	continuous
13	Night ventilation efficiency via windows	0~0.5	-	continuous

2.2. Research Methods

The parametric study of PH is achieved by sensitivity analysis (SA) and multiple regression analysis (MRA). The research framework is shown in Figure 2. First, PHPP is used to obtain valid samples conforming to the PHS. Then, the sensitivity (SRC value) and the model coefficient (R^2) of each parameter are obtained by the SRC method to determine the key parameters. Finally, multivariate regression analysis is used to establish the energy consumption meta-model. The samples extracted by Latin hypercube sampling (LHS) are used to verify the meta-model, and the PH database of each region is obtained. The optimization of PHs in different climate regions in China is studied, and the sensitive design parameters value of each climate zone is obtained.

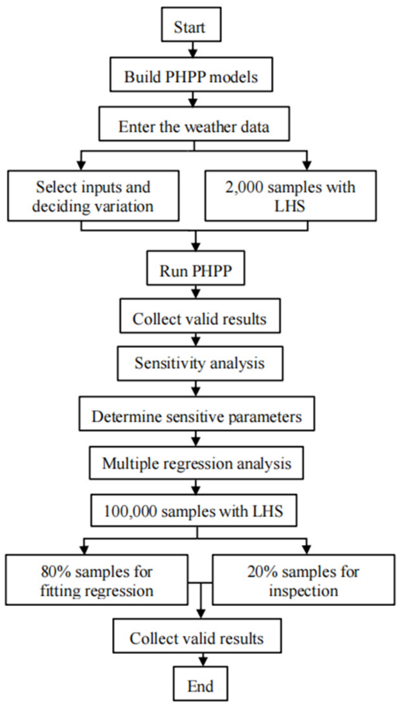


Figure 2. The framework of simulation and optimization.

2.2.1. Sensitivity Analysis

To explore the qualitative relationship between 13 design parameters and energy consumption, SA is used to determine the key parameters affecting energy consumption [45]. As a typical SA method [46], the SRC method considers the response of the entire parameter space and is widely used in building performance analysis [47–49]. Most importantly, the SRC method can provide valuable information about the relative influence of each design parameter on three energy consumption indices [50], and thus the SRC method is selected. The SRC value and the R^2 are calculated from Equations (1)–(4). The SRC value explains the weight of each input variable in the regression model, and the R^2 evaluates the reliability of the input and output of the model. The process of SA is calculated by the "sensitivity" package in the R program.

$$y_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} + \varepsilon_i \tag{1}$$

$$\sum_{i=1}^{N} (y_i - \overline{y})^2 = \sum_{i=1}^{N} (\hat{y}_i - \overline{y})^2 + \sum_{i=1}^{N} (\hat{y}_i - y)^2 \tag{2}$$

$$SRC_j = \beta_j \left[\sum_{i=1}^{N} \frac{(x_{ij} - \overline{x})^2}{N-1} \right]^{1/2} \left[\sum_{i=1}^{N} \frac{(y_i - \overline{y})^2}{N-1} \right]^{-1/2} \tag{3}$$

$$R_y^2 = \frac{\sum\limits_{i=1}^{N} (\hat{y}_i - \overline{y})^2}{\sum\limits_{i=1}^{N} (y_i - \overline{y})^2} \tag{4}$$

where β_0 is the constant, β_j is the regression coefficient, x_{ij} is the input/variable, y_i is the output/response, ε_i is an approximate error, $\overline{y}$ is the mean of y_i and $\hat{y}_i$ is the predicted value of y_i by the model.

2.2.2. Multiple Regression Analysis

To study the quantitative relationship between parameters and energy consumption, this paper establishes the meta-model by MRA. The meta-model is applied to obtain the key design parameter values suitable for China [51]. Different from classical regression model, the meta-model can consider the interaction between independent variables. Therefore, the classical regression model (5) is modified, and the form of the regression model remains unchanged as (6):

$$y_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \varepsilon_i \tag{5}$$

$$y_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \sum_{j' \geq j}^{n} \beta_{j;j'} x_j x_{j'} + \varepsilon_i \tag{6}$$

2.3. Simulation Verification of PHPP

In order to verify the accuracy of PHPP, we use the dynamic simulation software Design Builder (DB) to compare its result. We use model 1 and model 2 to simulate the representative cities: Harbin (SC), Beijing (C), Wuhan (HSCW), Guangzhou (HSWW) and Kunming (M). The 13 design parameters of two models are same and presented in Table 2. The calculation results are shown in Table 4.

Table 4 shows that the calculation relative error rate of PHPP and DB is between 4.3% and 8.7%. The results show that the energy consumption calculation error of PHPP and DB in each climate zone is less than 10%, which means that in this study, we can use PHPP to simulate building energy consumption in different climate zones.

Table 4. The calculation result of PHPP and Design Builder.

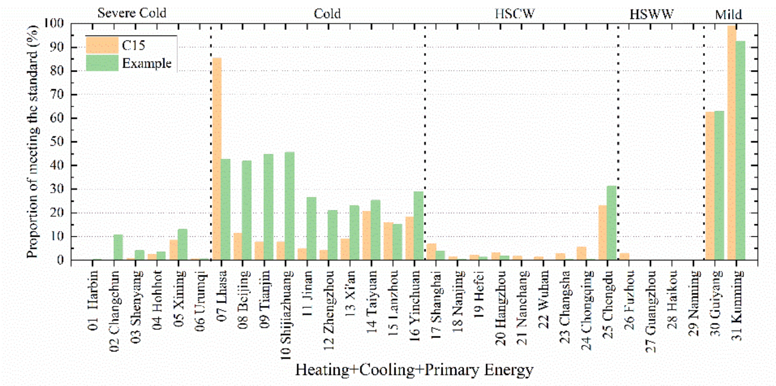
Location	Model 1			Model 2		
	Energy Consumption (kWh/m^2 a)		Relative Error Rate (%)	Energy Consumption (kWh/m^2 a)		Relative Error Rate (%)
	PHPP	DB		PHPP	DB	
Harbin	82	78.3	4.5	77.2	73.5	4.8
Beijing	70.6	73.8	−4.5	75.8	70.2	7.4
Wuhan	91.3	87.4	4.3	92.1	84.1	8.7
Guangzhou	98.5	92.9	5.4	93.7	89.7	4.3
Kunming	52.3	49.8	4.8	41.8	38.8	7.2

3. Results and Discussion

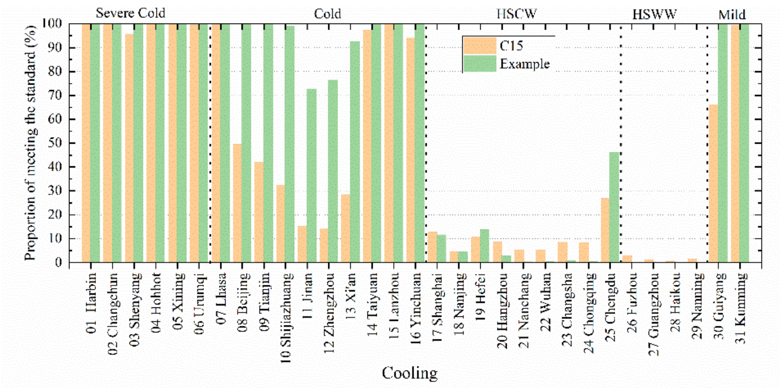
3.1. Energy Consumption Analysis

In this section, we analyze the extent to which building energy consumption in different regions can meet PHS. The percentage of satisfying the energy requirements of heating, cooling, primary energy and all three within PHS is calculated, respectively. The statistical results are shown in Figure 3.

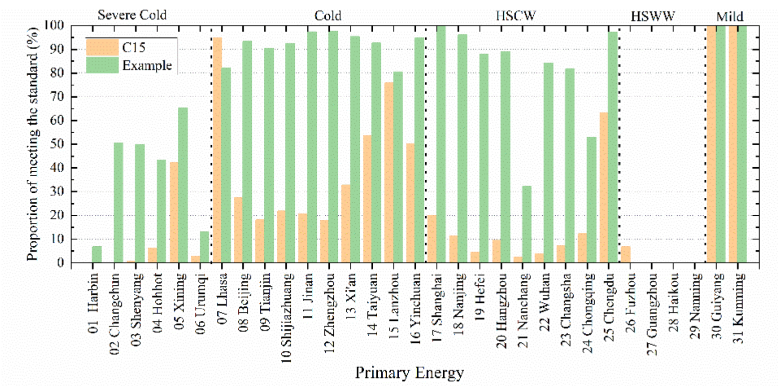
Figure 3 shows that the proportion of the PH cases that satisfy the standards in China's different climate zones varies greatly. The results show that the warmer the climate is, the easier it is to meet the heating demand. Due to the low HDDs in HSCW, HSWW and M areas, the heating energy consumption is relatively low. Therefore, Figure 3a shows that the average proportion meeting the heating standard is HSWW > M > HSCW > C > SC. Similarly, for cooling demand, since heating is mainly considered in C and SC, the cooling energy consumption is relatively low, so the average fill rate in Figure 3b is M > SC > C > HSCW > HSWW. Among them, the building energy consumption is low in the M area, which meets the requirement. For the same standard, the energy consumption of PH in the same climate zone is greatly affected by the building type, such as the primary energy demand: Villa buildings are easier to realize PH than high-rise buildings in Figure 3d. In the initial setting, the high-rise residential (C15) consumes more electricity than the villa (example) setting in public areas such as elevators. In addition to the sub energy consumption, it also considers the three at the same time. Figure 3d shows that PHs are easy to be realized in M areas, followed by some C areas; meanwhile, the satisfaction rate of the villa is generally higher than the high-rise. As the latitude of C areas are close to Germany, but the temperature is lower, only parts can meet the requirements. In summary, in addition to M areas, it is difficult for PHs to fully meet the energy consumption requirements in China. Therefore, it is necessary to optimize the building design parameters to achieve the PHS in all Chinese climates.



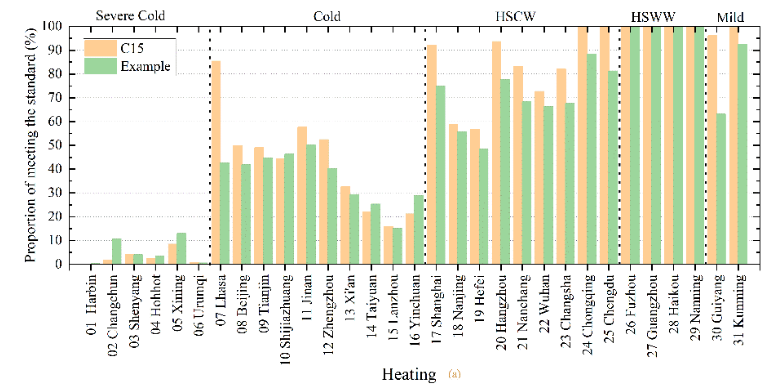
(**a**) Three energy consumption satisfaction rate



(**b**) Cooling satisfaction rate



(**c**) Primary energy satisfaction rate



(**d**) Heating satisfaction rate

Figure 3. The proportion of samples meeting different energy requirements of PHS in 31 cities.

3.2. Sensitivity Analysis

3.2.1. General Parameter Analysis

Figure 4a–f shows the sensitivity of each design parameter for the three energy consumption outputs, namely heating, cooling and primary energy consumption in the eight representative cities. For both types of buildings, the length of each color bar indicates the size of the SRC, a positive value indicates that the parameter value will result in an increase in energy consumption, and vice versa. While SRC < 0.1, there is almost no relationship between input and output. For the SC and C regions, the sensitivity analysis results show that the important parameters are WU, SHGC, HERE, UG and BCU. However, for the HSCW, in addition to the five parameters mentioned above, HURE is also an important parameter. For the HSWW, there are large fluctuations that the key parameters are only SHGC and HURE. As shown in 3.1, because of low energy consumption, the design parameters in M areas do not need to be further optimized, so the sensitivity of design parameters in this area is not considered.

3.2.2. Parameter Analysis for Different Climates

Figure 4a–d shows that the parameters with large SRC values are WU, SHGC, BCU, UG and HERE. It can be seen from Section 3.1 that heating is mainly considered in SC and C areas. Meanwhile, the temperature difference between indoor and outdoor in winter is large, so the heat transfer coefficient of the envelope (WU, BCU and UG) can effectively reduce the heating demand. PH has changed the traditional heating form, mainly heating by ventilation, and using fresh air heat recovery can save heating. At the same time, it can effectively use solar radiation to gain heat. Other parameters have less impact on energy consumption in SC and C areas. The climate in the HSCW region is complex, hot and humid in summer. Therefore, it is necessary to increase HURE to reduce the energy consumption of dehumidification. Due to low temperature and insufficient sunshine in winter, UG and SHGC should be considered. At the same time, the appropriate heat transfer coefficient of the envelope takes into account heat preservation in summer and heat insulation in winter. Therefore, the sensitive parameters are WU, HERE, UG, SHGC, HURE, and BCU in the HSCW region. According to energy consumption analysis, the HSWW area mainly considers the cooling, and the solar radiation intensity and humidity are large. Therefore, it is necessary to increase the HURE to reduce dehumidification energy consumption and choose appropriate SHGC values to reduce solar heat. Therefore, Figure 4g shows sensitive parameters for HURE and SHGC in the SHWW region. In summary, SHGC is considered to be the most influential factor in all climate zones, although SHGC regulation is relatively contradictory in HSCW. Second, WU, BCU, UG and HERE are important for areas that require heating, and HURE is significant for areas that require cooling and dehumidification.

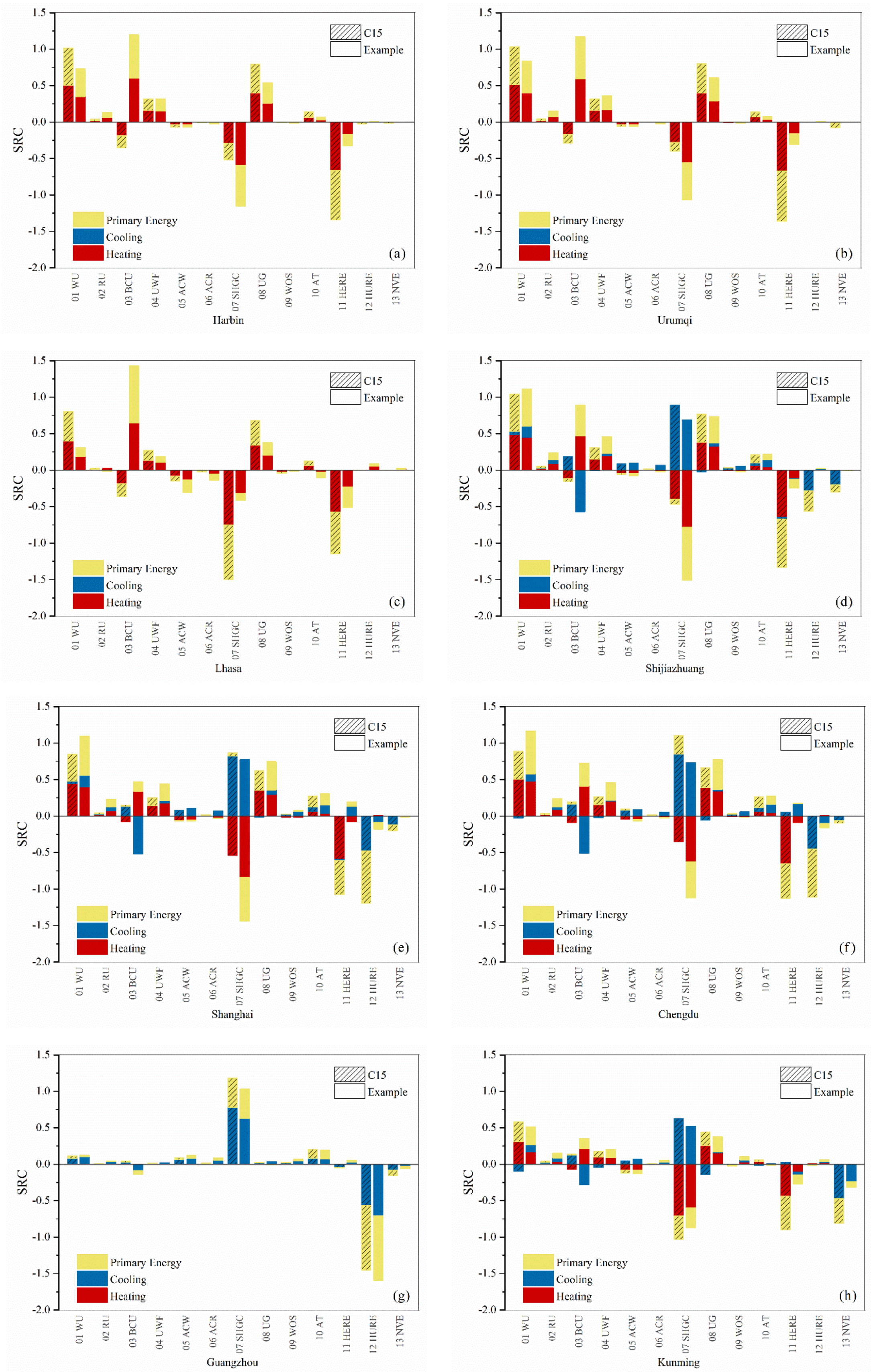


Figure 4. SRC values of parameters on heating, cooling and primary energy demand in eight cities. (**a**) Harbin, (**b**) Urumqi, (**c**) Lhasa, (**d**) Shijiazhuang, (**e**) Shanghai, (**f**) Chengdu, (**g**) Guangzhou, (**h**) Kunming.

3.2.3. Parameter Analysis for Different Building Types

For SC and C areas, except UG, other important parameters have obvious differences in the two building types. Among them, WU and HERE have larger SRC values in high-rise buildings. Due to the larger external wall area and fresh air heat recovery, the impact on the high-rise is greater. On the contrary, SHGC is more sensitive in the villa, because the solar heat gaining in the villa accounts for a large proportion of heating demand. BCU has the opposite SRC value in the two types of buildings. Because the villa directly contacts the ground and high-rise buildings have a basement, the villa loses a lot of heat through the ground, while high-rise buildings reduce heat loss through the basement, so BCU has the opposite effect. In the HSCW area, because of cooling in the summer and heating in the winter, SHGC has opposite SRC values in the two buildings for primary energy demand. Therefore, the SHGC adjustment is relatively contradictory. HURE and HERE are more sensitive in high-rise buildings. Because high-rise buildings need a large amount of fresh air for cooling and heating, they can obtain more heat and moisture recovery. For the HSWW area, there is little difference between sensitive parameters among different types of buildings.

Table 5 shows the R^2 of the energy consumption regression model for high-rise and villa buildings in eight representative cities. Except for Kunming, R^2 is greater than 0.9 in other areas, indicating that the regression model has a high degree of reliability. From 3.1, the building energy consumption is low in Kunming, and the energy consumption varies greatly under different parameter combinations, so the fitting accuracy is not accurate enough. Furthermore, the heating demand in Guangzhou and the cooling demand in Harbin, Urumqi and Lhasa are too low to be shown in the Table 5.

Table 5. Variation of R2 value with SRC method for three outputs.

City	Building Type	Heating Demand	Cooling Demand	Primary Energy Demand
Harbin	Example	0.988	-	0.978
	C15	0.988	-	0.995
Urumqi	Example	0.988	-	0.984
	C15	0.997	-	0.995
Lhasa	Example	0.900	-	0.847
	C15	0.988	-	0.982
Shijiazhuang	Example	0.989	0.849	0.968
	C15	0.997	0.975	0.990
Shanghai	Example	0.939	0.952	0.769
	C15	0.990	0.982	0.982
Chengdu	Example	0.981	0.897	0.950
	C15	0.993	0.993	0.991
Guangzhou	Example	-	0.997	0.992
	C15	-	0.996	0.998
Kunming	Example	0.693	0.447	0.364
	C15	0.863	0.665	0.554

3.3. Meta-Model Analysis

3.3.1. Determine the Value of Key Parameters

Taking high-rise buildings in Shijiazhuang as an example, firstly the valid samples are calculated by PHPP from 2000 samples. Then, 80% of the valid data are modeled, and the remaining are used to test the accuracy of the model. As shown in Figure 5a, the calculation results of the primary energy regression equation and PHPP are highly fitted, and the accuracy of the regression equation is as high as 99.7%. The regression equation of the agent is used to calculate the energy consumption value corresponding to 100,000 sample numbers. Three samples with energy consumption values satisfying the German PHS are taken as the PH database of the building type in the region. The samples are extracted by LHS, so the data are discontinuous and random, as shown in Figure 5b. To obtain the influence of a single factor on the objective function, dimension reduction was carried out in Figure 5c. The sample is red, and the one that is not satisfied is gray. The value range of SHGC is between 0.1 and 1.0. The value range is divided into nine equal parts. The frequency of 100,000 samples in each interval is met, as shown in Figure 6d. When the frequency of a certain interval is greater than $(0.9 - 0.1)/9 = 0.1$ (the red horizontal line in the figure), it is more suitable to establish a passive house in the interval of 0.5–1.0 in the SHGC. The trends shown in Figure 5c,d are different, because, in addition to primary energy, the effects of SHGC on cooling and heating need to be considered.

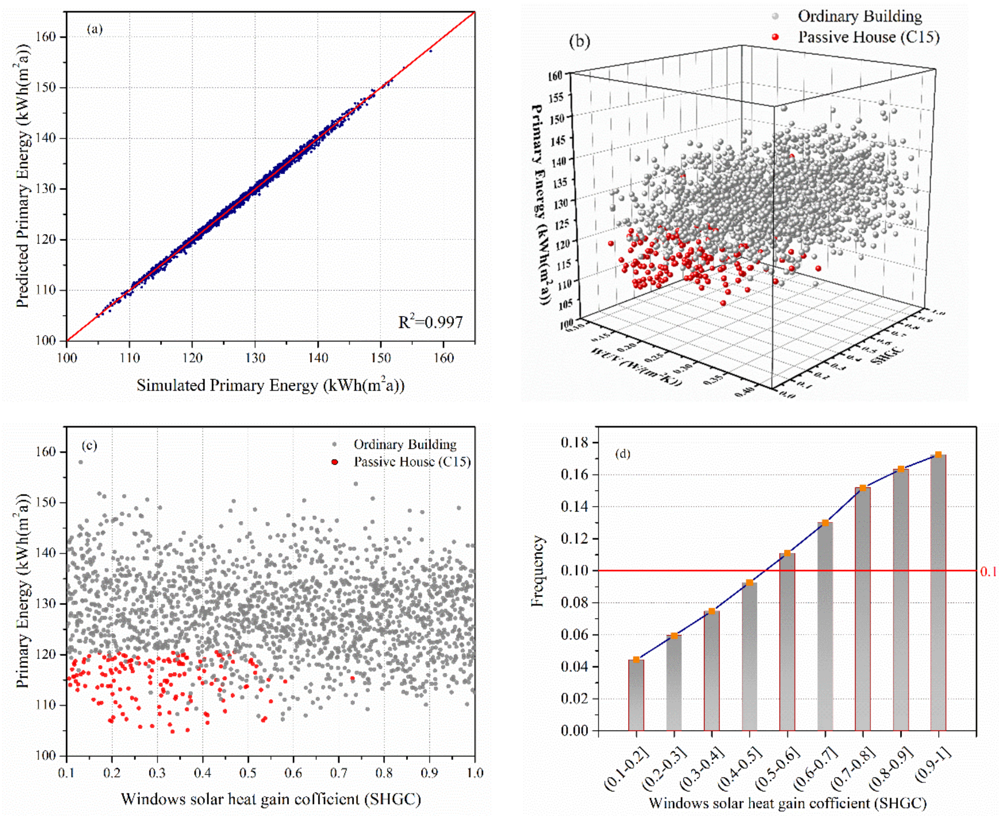


Figure 5. Meta-model to determine PH parameter range method. (**a**) Model validation, (**b**) Parameter dimension reduction, (**c**) Influence of SHGC on primary energy, (**d**) Determination of the range of SHGC.

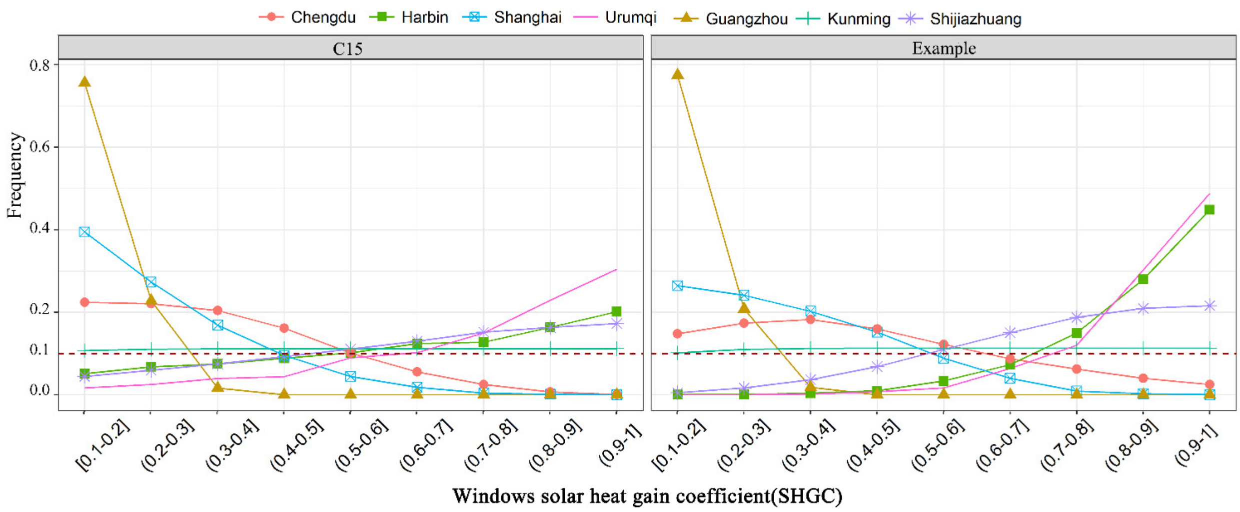


Figure 6. Distribution of the PH samples according to SHGC.

3.3.2. Analyze Key Parameter Value

According to Section 3.2, the sensitive parameters of PH are WU, BCU, SHGC, UG, HERE and HURE. The method in Section 3.3.1 is used to get the appropriate value of each sensitive parameter under different climate conditions. Taking SHGC as an example, Figure 6 analyzes the appropriate value range of key parameters in seven representative cities.

According to the red horizontal line, reasonable SHGC values can meet the requirements of PH in various climatic regions. According to the frequency, SHGC has the same influence on high-rise buildings and villa buildings in Figure 6. More than 75% of cases that realize the PHS have an SHGC value between 0.1–0.2 in Guangzhou, and the smaller the value, the better. However, the larger the value in Harbin, Urumqi and Shijiazhuang, the easier it is to realize PH. Because C and SC regions need solar heat gain to reduce heat load. In Shanghai and Chengdu, parameter frequency is a relatively stable trend, due to the hot summer and cold winter. For Kunming, the frequency curve is above the red horizontal line, so any SHGC value meets the requirements of PH. In conclusion, the value of SHGC depends on geographical location and climate, and it contributes a lot to the refrigeration and dehumidification in HSWW and HSCW areas and the heating in SC and C areas. The optimal values and ranges of the 31 city sensitive parameters are presented in Appendices A and B.

3.3.3. Chinese PH Design Zoning

According to the results (Appendices A and B) calculated by the SRC and meta-model, 31 cities are reclassified into 7 PH zones (Table 6 and Figure 7) in China. The recommended values of the key design parameters for the optimization of different PH design areas are shown in Table 6. According to the comparison and summary of important design parameters, similar cities are divided into the same area. The recommended range is based on the range above the average horizontal line calculated in Section 3.3. The "-" in the table indicates that this design parameter is not suitable for use in the area, such as heat recovery in M and HSWW zones.

Table 6. Design zoning and key design parameter range of PH.

Zone No.	City	WU	BCU Basement		SHGC	UG	HERE	HURE
			With	Without				
1	Harbin, Changchun, Shenyang, Hohhot, Xining	0.1–0.2	1.22–2	0.18–0.82	0.6–1	0.1–0.7	0.7–0.95	-
2	Beijing, Tianjin, Shijiazhuang, Jinan, Zhengzhou, Xi'an, Taiyuan, Lanzhou, Yinchuan	0.1–0.24	0.18–2	0.18–1.14	0.5–1	0.1–0.7	0.6–0.95	-
3	Shanghai, Nanjing, Hangzhou, Nanchang, Wuhan, Hefei, Changsha, Chongqing	0.1–0.2	1.3–2	1.3–2	0.1–0.5	0.1–0.7	0–0.4	0.5–0.9
4	Fuzhou, Guangzhou, Haikou, Nanning	0.1–0.24	0.18–2	0.18–2	0.1–0.3	0.1–0.7	-	0.7–0.9
5	Lhasa, Guiyang, Kunming	0.1–0.4	0.18–2	0.18–2	0.1–1	0.1–1	-	-
6	Urumqi	0.1–0.18	1.38–2	0.18–0.66	0.7–1	0.1–0.5	0.6–0.95	-
7	Chengdu	0.1–0.2	1.14–2	0.18–2	0.1–0.5	0.1–0.9	0.45–0.95	0.6–0.9

The geographical layout between the residential PH design zones and thermal partition is distinct, especially Lhasa, Chengdu and Urumqi (Figure 7). The first and second zones cover parts of the C and SC regions, respectively. The third zone, except Chengdu and its surrounding areas, mainly covers HSCW regions. The fourth zone covers all HSWW areas. It is worth noting that the fifth region covers M and some C areas. The design needs to reduce the heating load; however, the heat load can be solar energy, so there is almost no energy consumption in the area. The sixth zone is composed of Urumqi and its surrounding areas. The climate is dry, the summer is ho and the temperature difference between day and night is large. Therefore, the indoor needs to be appropriately supplemented to prevent excessive drying, and the wall needs to use heat storage materials to store the heat during the day and release it at night. The seventh zone covers Chengdu and its surrounding areas. The district has high outdoor humidity, surrounded by mountains and has a complex terrain. There is a pattern of coexistence of two climates: Warm winter and cold west. Due to the lack of weather data from neighboring cities, the boundaries of the seventh are marked with dashed lines to show areas of uncertainty.

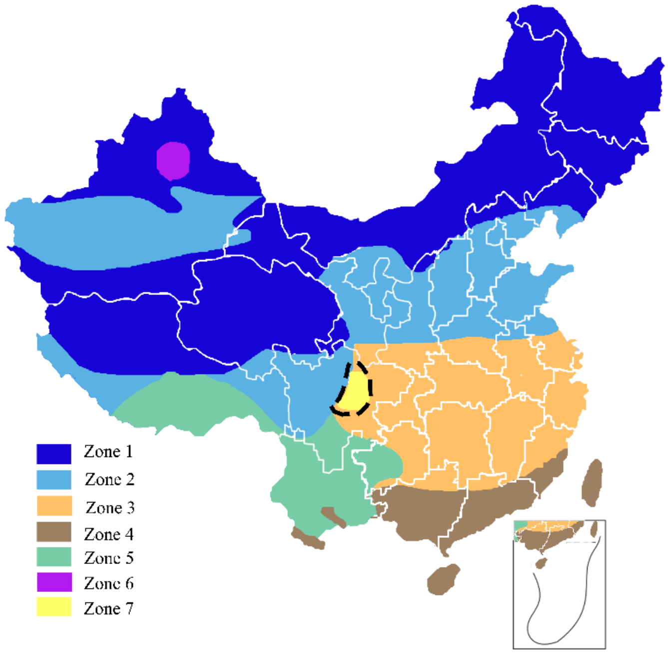


Figure 7. 31 cities in China are reclassified into seven PH zonings.

In order to verify the reliability of the PH design zone, another representative city is selected in each zone for verification. The specific method uses the LHS extraction of 100,000 samples to be substituted into the regression model obtained in the third part within the recommended range, and compares the quantity satisfying the condition to the quantity satisfying the condition within the original range value of the design parameter. The results are presented in Table 7. The new PH design zone reduces building energy consumption in the architectural design stage in the majority of areas. Especially in the area around Urumqi, the models that meet the PHS have increased nearly 30 times.

Table 7. Optimization effect of PH zoning.

Zone No.	City	The Number of Cases	Cases after Optimization	Rate of Change (%)
1	Harbin	2330	71,062	2950
2	Shijiazhuang	37,653	99,865	165
3	Shanghai	15,603	91,317	485
4	Guangzhou	3408	64,478	1792
5	Kunming	-	-	0
6	Urumqi	2194	67,200	2963
7	Chengdu	48,648	99,991	106

4. Conclusions

To solve the climate adaption of PH in China, we develop two PH models for high-rise buildings and villas and performs sensitive analysis of 13 design parameters in 31 cities that covering five Chinese climate zones. Moreover, a reasonable range of sensitive parameters is obtained by the energy consumption meta-model. Based on the parametric analysis, the design zoning of China's residential PHs is finally proposed. The conclusions are summarized as below:

1. As the energy consumption is greatly affected by climate conditions, the satisfaction rates of energy consumption index vary with climate regions. SC, C areas are easy to meet the cooling energy requirements; HSWW, followed by HSCW areas are relatively easy to meet the heating energy requirements. Building energy consumption in M areas are low and easy to meet PHS. Except for the M, it is difficult to achieve PHs in all climatic regions in China.
2. The sensitivity of the key design parameters in different climate regions are different. SHCG is the most effect parameter for all climatic zones, followed by WU, BCU, UG, and HERE for heating zones. Furthermore, HURE is the key parameter in areas with high humidity. BCU has the largest difference in sensitivity to different types of buildings, followed by SHCG, especially in HSCW areas. Among the 13 design parameters, ACW and ACR have the least influence.
3. The proposed residential PH design zoning is not consistent with traditional Chinese climate region. According to the difference of sensitive parameters, Chengdu with its surrounding areas and Urumqi with its surroundings are divided into two climate zones. Because HERE of Chengdu and its surrounding areas (0.45 ~ 0.95) is much higher than that of other areas in hot summer and cold winter areas (0 ~ 0.4), the optimized passive design can significantly reduce the annual heating load of Urumqi and its surrounding areas, and even replace the air conditioning system of Urumqi with high solar radiation. After optimizing the parameters, the number of buildings meeting the PHS based on the proposed design zoning has increased dramatically. Seven zones are proposed with optimized values for key design parameters. Therefore, the design zoning of PH in China is put forward, which can guide the design of PH as well as enhance the application of PH in China.
4. The important challenge of this work is to propose residential PH design zoning. Architects can directly determine the appropriate passive design measures within the scope of zoning without simulation calculation. In addition, these results can be used as a reference for further optimization research, which can guide the design of PH as well as enhance the application of PH in China.

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Appendix A

Table A1. Recommended value range for major design parameters in 31 cities.

City	Building Type	WU W/(m^2 K)	BCU W/(m^2 K)	SHGC	UG W/(m^2 K)	HERE	HURE
Harbin	Example	0.1–0.22	0.18–0.74	0.7–1.0	0.1–0.7	0.5–0.95	-
	C15	0.1–0.2	1.22–2.0	0.6–1.0	0.1–0.6	0.7–0.95	-
Changchun	Example	0.1–0.24	0.18–0.98	0.7–1.0	0.1–0.7	0.5–0.95	-
	C15	0.1–0.2	1.22–2.0	0.7–1.0	0.1–0.7	0.65–0.95	-
Shenyang	Example	0.1–0.22	0.18–0.74	0.7–1.0	0.1–0.7	0.6–0.95	-
	C15	0.1–0.2	1.22–2.0	0.6–1.0	0.1–0.6	0.7–0.95	-
Hohhot	Example	0.1–0.2	0.18–0.82	0.7–1.0	0.1–0.7	0.6–0.95	-
	C15	0.1–0.2	1.14–2.0	0.6–1.0	0.1–0.6	0.7–0.95	-
Xining	Example	0.1–0.24	0.18–0.9	0.7–1.0	0.1–0.7	0.5–0.95	-
	C15	0.1–0.2	1.14–2.0	0.6–1.0	0.1–0.7	0.65–0.95	-
Urumqi	Example	0.1–0.18	0.18–0.66	0.7–1.0	0.1–0.6	0.55–0.95	-
	C15	0.1–0.18	1.38–2.0	0.7–1.0	0.1–0.5	0.75–0.95	-
Lhasa	Example	0.1–0.4	0.18–2.0	0.5–1.0	0.1–1.0	0.0–0.95	-
	C15	0.1–0.4	0.18–2.0	0.4–1.0	0.1–1.0	0.0–0.95	-
Beijing	Example	0.1–0.4	0.18–2.0	0.4–1.0	0.1–1.0	0.0–0.95	-
	C15	0.1–0.24	0.18–2.0	0.1–0.6	0.1–0.8	0.55–0.95	-
Tianjin	Example	0.1–0.26	0.18–2.0	0.5–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.22	0.18–2.0	0.1–0.5	0.1–0.7	0.5–0.95	-
Shijiazhuang	Example	0.1–0.24	0.18–1.14	0.6–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.24	0.18–2.0	0.6–1.0	0.1–0.8	0.5–0.95	-
Jinan	Example	0.1–0.24	0.18–2.0	0.4–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.22	0.98–2.0	0.1–0.7	0.1–0.7	0.55–0.95	-
Zhengzhou	Example	0.1–0.24	0.18–0.98	0.6–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.24	0.18–2.0	0.6–1.0	0.1–0.8	0.55–0.95	-
Xi'an	Example	0.1–0.24	0.18–1.22	0.6–1.0	0.1–0.7	0.0–0.95	-
	C15	0.1–0.22	1.06–2.0	0.1–0.6	0.1–0.8	0.55–0.95	-
Taiyuan	Example	0.1–0.24	0.18–0.98	0.7–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.22	0.18–2.0	0.6–0.7	0.1–0.7	0.55–0.95	-
Lanzhou	Example	0.1–0.22	0.18–0.9	0.7–1.0	0.1–0.7	0.0–0.95	-
	C15	0.1–0.22	0.18–2.0	0.6–1.0	0.1–0.7	0.6–0.95	-
Yinchuan	Example	0.1–0.26	0.18–0.98	0.6–1.0	0.1–0.8	0.0–0.95	-
	C15	0.1–0.22	0.18–2.0	0.6–1.0	0.1–0.7	0.6–0.95	-
Shanghai	Example	0.1–0.22	1.06–2.0	0.1–0.5	0.1–0.8	0.0–0.5	0.45–0.9
	C15	0.1–0.24	1.14–2.0	0.1–0.4	0.1–0.8	0.0–0.95	0.5–0.9
Nanjing	Example	0.1–0.18	0.9–2.0	0.1–0.5	0.1–0.6	0.35–0.95	0.5–0.9
	C15	0.1–0.22	1.3–2.0	0.1–0.4	0.1–0.7	0.6–0.95	0.55–0.9
Hefei	Example	0.1–0.2	0.18–2.0	0.1–0.6	0.1–0.7	0.0–0.95	0.5–0.9
	C15	0.1–0.2	0.22–2.0	0.1–0.4	0.1–0.7	0.6–0.95	0.6–0.9
Hangzhou	Example	0.1–0.2	1.22–2.0	0.1–0.3	0.1–0.7	0.0–0.4	0.5–0.9
	C15	0.1–0.2	1.3–2.0	0.1–0.3	0.1–0.7	0.55–0.95	0.65–0.9
Nanchang	Example	0.1–0.2	1.3–2.0	0.1–0.4	0.1–0.6	0.0–0.35	0.65–0.9
	C15	0.1–0.18	1.62–2.0	0.1–0.3	0.1–0.5	0.3–0.95	0.75–0.9
Wuhan	Example	0.1–0.2	1.3–2.0	0.1–0.4	0.1–0.6	0.0–0.35	0.6–0.9
	C15	0.1–0.16	1.46–2.0	0.1–0.3	0.1–0.7	0.0–0.7	0.5–0.9
Changsha	Example	0.1–0.2	1.22–2.0	0.1–0.4	0.1–0.7	0.0–0.4	0.5–0.9
	C15	0.1–0.2	1.46–2.0	0.1–0.3	0.1–0.7	0.35–0.55	0.7–0.9
Chongqing	Example	0.1–0.24	1.3–2.0	0.1–0.3	0.1–0.9	0.0–0.35	0.6–0.9
	C15	0.1–0.22	1.3–2.0	0.1–0.3	0.1–0.7	0.0–0.95	0.65–0.9
Chengdu	Example	0.1–0.26	0.18–2.0	0.1–0.6	0.1–0.8	0.0–0.95	0.5–0.9
	C15	0.1–0.26	1.14–2.0	0.1–0.5	0.1–1.0	0.0–0.95	0.65–0.9
Fuzhou	Example	0.1–0.22	1.14–2.0	0.1–0.3	0.1–1.0	-	0.65–0.9
	C15	0.1–0.4	0.18–2.0	0.1–0.3	0.1–1.0	-	0.6–0.9
Guangzhou	Example	0.1–0.2	0.18–2.0	0.1–0.3	0.1–0.8	-	0.45–0.9
	C15	0.1–0.2	0.18–2.0	0.1–0.3	0.1–0.8	-	0.55–0.9
Haikou	Example	0.1–0.22	0.18–1.06	0.1–0.3	0.1–0.7	-	0.7–0.9
	C15	0.1–0.28	0.18–2.0	0.1–0.3	0.1–1.0	-	0.65–0.9
Nanning	Example	0.1–0.24	0.18–2.0	0.1–0.4	0.1–0.7	-	0.75–0.9
	C15	0.1–0.24	0.18–2.0	0.1–0.3	0.1–0.8	-	0.7–0.9
Guiyang	Example	0.1–0.24	0.18–1.06	0.6–1.0	0.1–0.8	-	-
	C15	0.1–0.26	0.18–2.0	0.1–0.7	0.1–1.0	-	-
Kunming	Example	0.1–0.4	0.18–2.0	0.1–1.0	0.1–1.0	-	-
	C15	0.1–0.4	0.18–2.0	0.1–1.0	0.1–1.0	-	-

Appendix B

Table A2. Recommended values for major design parameters in 31 cities.

City	Building Type	WU W/(m^2 K)	BCU W/(m^2 K)	SHGC	UG W/(m^2 K)	HERE	HURE
Harbin	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Changchun	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Shenyang	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Hohhot	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Xining	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Urumqi	Example	0.1	0.18	1.0	0.1	0.95	-
	C15	0.1	2.0	1.0	0.1	0.95	-
Lhasa	Example	0.4	0.18	0.6	1.0	0.0	-
	C15	0.4	2.0	0.6	1.0	0.0	-
Beijing	Example	0.4	0.18	0.6	1.0	0.8	-
	C15	0.1	2.0	0.35	0.1	0.8	-
Tianjin	Example	0.1	0.18	0.7	0.1	0.8	-
	C15	0.14	2.0	0.1	0.1	0.8	-
Shijiazhuang	Example	0.1	0.18	0.8	0.1	0.8	-
	C15	0.1	2.0	1.0	0.1	0.8	-
Jinan	Example	0.1	0.18	0.5	0.1	0.8	-
	C15	0.1	2.0	0.1	0.1	0.8	-
Zhengzhou	Example	0.1	0.18	0.8	0.1	0.8	-
	C15	0.1	2.0	1.0	0.1	0.8	-
Xi’an	Example	0.1	0.18	0.8	0.1	0.8	-
	C15	0.1	2.0	0.45	0.1	0.8	-
Taiyuan	Example	0.1	0.18	1.0	0.1	0.8	-
	C15	0.1	2.0	1.0	0.1	0.8	-
Lanzhou	Example	0.1	0.18	1.0	0.1	0.8	-
	C15	0.1	2.0	1.0	0.1	0.8	-
Yinchuan	Example	0.1	0.18	0.8	0.1	0.8	-
	C15	0.1	2.0	1.0	0.1	0.8	-
Shanghai	Example	0.1	2.0	0.1	0.1	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.0	0.9
Nanjing	Example	0.1	2.0	0.1	0.1	0.8	0.9
	C15	0.1	2.0	0.1	0.1	0.8	0.9
Hefei	Example	0.1	2.0	0.3	0.1	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.8	0.9
Hangzhou	Example	0.1	2.0	0.1	0.4	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.8	0.9
Nanchang	Example	0.1	2.0	0.1	0.1	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.8	0.9
Wuhan	Example	0.1	2.0	0.1	0.1	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.0	0.9
Changsha	Example	0.1	2.0	0.1	0.1	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.4	0.9
Chongqing	Example	0.1	2.0	0.1	0.5	0.0	0.9
	C15	0.1	2.0	0.1	0.1	0.0	0.9
Chengdu	Example	0.12	2.0	0.35	0.3	0.0	0.9
	C15	0.1	2.0	0.3	1.0	0.0	0.9
Fuzhou	Example	0.14	2.0	0.1	1.0	-	0.9
	C15	0.4	2.0	0.1	1.0	-	0.9
Guangzhou	Example	0.14	2.0	0.1	0.5	-	0.9
	C15	0.1	2.0	0.1	0.35	-	0.9
Haikou	Example	0.14	0.1	0.1	0.7	-	0.9
	C15	0.14	2.0	0.1	1.0	-	0.9
Nanning	Example	0.14	2.0	0.1	0.1	-	0.9
	C15	0.1	2.0	0.1	0.1	-	0.9
Guiyang	Example	0.4	0.1	1.0	0.1	-	-
	C15	0.1	2.0	0.45	1.0	-	-
Kunming	Example	0.4	2.0	1.0	1.0	-	-
	C15	0.4	2.0	1.0	1.0	-	-

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