Multi-objective optimization design for windows and shading configuration: considering energy consumption, thermal environment, visual performance and sound insulation effect

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Abstract

The window and shading configuration is the weak link of heat insulation in the outer protective structure. And it is also an important means of visual performance, which plays an important part in building energy savings. Resulting from the influence of weather and solar radiation, there are contradictions among the energy consumption, visual performance and thermal environment. Therefore, in order to optimize the three factors, an effective optimization method is necessary. For the window design, the existing studies mostly focus on the analysis of energy consumption performance, less on the sound insulation performance. In addition, the optimal configuration of windows and shading system under different climatic regions and orientations has been solved. In this paper, a multi-objective optimization model considering building energy consumption, thermal environment and visual performance was proposed by introducing window orientation, window–wall ratio, window configuration, shading angle and length parameters. And it uses the non-dominated sequencing genetic algorithm NSGA-II and energy simulation software EnergyPlus. The corresponding Pareto solution set was obtained from the assumed room in a cold region, hot summer and cold winter region and hot summer and warm winter region, respectively. The optimal recommended values of window parameters in each direction were determined by analyzing the Pareto solution set. The effectiveness of the multi-objective optimization model is proved by using the linear weighted sum method, and the optimization method of sound insulation effect is discussed. The optimization model in this paper is helpful for designers to choose the optimal design scheme, so that it can comply with the design requirements in terms of energy consumption, thermal environment, visual performance and achieve the overall optimal performance.

Keywords Multi-objective optimization · Windows and shading configuration design · Energy consumption · Thermal environment · Visual performance · Sound insulation effect

Introduction

Background

In recent years, the building has become one of the largest energy consumption departments. Its energy consumption has accounted for 36% of global energy consumption [1]. With energy shortage and high energy cost, the modern construction industry pays more attention to energy efficiency, countries have introduced the corresponding energy-saving policy and standards, and the energy saving as the architectural design is an important consideration, such as DGNB, BREEAM, LEED and CASBEE, and these developed countries formulate and introduce corresponding policies early to promote the energy efficiency. Although China and other developing states started late, they gradually paid more attention to it. They clearly proposed implementing the plan of building energy efficiency improvement and the development of the whole industrial chain of green buildings. China presented the evaluation standard of China's green standard in 2018 [2]. The importance of building energy efficiency optimization is becoming ever more prominent.

It is generally believed that the early stages of building design can determine 80% of the cost and performance of a building. The form and the envelope of the building are important parts in initial design decisions. They are difficult

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to change in the future [3], so the design stage is crucial in the building process. Among the many structural elements of architectural design, the window is a transparent maintenance structure. The sunlight can enter the room through it, which is an essential way of visual performance. The visual performance is an important aspect of indoor environment quality evaluation. Good indoor daylighting can not only have a positive impact to the user cortisol, benefit to people's health and improve the productivity [4], but also reduce the energy consumption of lighting. At the same time, solar radiation can bring indoor heat energy to reduce heating energy consumption in winter. However, excessive sunlight may cause glare and unnecessary reflection and also lead to indoor overheating in summer. Thus, it reduces indoor thermal environment and increases summer cooling energy consumption. In addition, due to the material and thickness of the window, the insulation and sound insulation effect are poor compared to the opaque envelope. 75% heat dissipation and increase occur in the external maintenance structure [5], and the window is one of the weak links [6]. Windows' heat transfer coefficient is usually 5 more times than other building maintenance components, accounting for 60% of the total energy consumption of the building [7]. So it has always been the focus of designers' design.

Building physical properties include building optics, thermal engineering and acoustics [8]. Building sound insulation is also one of the principal evaluation indexes of building envelope, because noise may cause systemic damage to the human body. At present, most of the researches on window optimization mainly focus on the energy performance and cost of buildings. The lighting effect is in the next place. The researches on window sound insulation are relatively few [6]. At present, various countries have adopted a series of standards for building acoustic environment. Experiment proved that about 90% of the noise is through the window into the room. In order to enhance the sound insulation effect of the window, usually use methods such as increase the thickness and reduce the window area method. And the change of these parameters, such as the window size and the thickness of materials, can affect the sun radiation, heat insulation and sound insulation differently. So the window optimization design is a complex optimization problem.

In the design of windows, the methods of improving the performance of windows are usually adopted to create a good indoor thermal environment and improve the energy efficiency of buildings, such as using double-layer glass to increase thermal resistance and using coated glass to control sunlight [9]. At present, designers are more inclined to use glass in a large area for good elevation visual effect, especially in office buildings [10]. That will lead to the decrease in the overall *U*-value of the building envelope and the excessive acquisition of solar radiation energy in summer [11]. It is undoubtedly not conducive to reducing building

energy consumption and difficult to meet the requirements of building energy saving and improving indoor comfort only by using high-performance windows. So it is difficult to meet the requirements of building energy saving and indoor comfort. Many studies have taken sunshade equipment into account in window design [12]. Shading equipment can not only reduce excessive solar light and reduce glare and improve visual comfort [13], but also reduce summer heat entering the room through solar radiation and increase lighting energy consumption and winter heating energy consumption [14]. It can be seen that windows and sunshade equipment promote and contradict each other in building energy consumption and visual performance. Therefore, it is particularly important to choose reasonable sunshade equipment and windows.

In order to realize a reasonable design, we usually need building energy consumption simulation tools and optimization methods to improve the building design. In order to find the optimal or near-optimal design scheme, post-processing methods such as Pareto frontier are normally applied [15], which requires designers to have dependable computer programming requirements, but most designers do not touch the relevant methods. They utilize some outdated and inefficient methods to solve the problem of building energy-saving design [16], so designers need a practical and effective building energy-saving optimization design tool.

Existing researches

Research on optimal design method of building energy saving

It is known that the optimization of windows and sunshade equipment often designs multiple parameters, and each parameter is within a certain range of values. The use of enumeration method often consumes a lot of calculation time. So many scholars introduce single-objective optimization method in the architectural design stage and use the optimization of the building structure to achieve energy saving and environmental protection. Susorova et al. [17] studied the effects of window orientation, room size and window-to-wall ratio (WWR) on the energy consumption performance of office buildings. Li et al. [18] used energy prediction and analysis model to optimize the building facade to reduce the energy consumption of the building. However, the above studies all take a single objective as the optimization object. In reality, there are often some conflicts between multiple objectives, such as the interaction between building energy consumption and indoor natural lighting. Therefore, the building energy efficiency optimization based on single-objective optimization has been unable to meet the needs of the current economic and social development. The research shows that the individual optimization of each field may

have an adverse impact on the overall design of the building [19]. Therefore, the multi-objective energy-saving optimization method considering multi-objective optimization at the same time has attracted the attention of scholars.

In order to realize the best scheme of building energy-saving design based on multi-objective optimization, scholars usually combine building performance simulation software with mathematical optimization tools and use professional knowledge in many fields. That can contribute to seek a comprehensive and efficient multi-objective optimization method for building energy conservation. This method has become a common research method in the field of building energy consumption. Wu et al. [20] adopted the combination of non-dominated sorting genetic algorithm (NSGA-II) and architectural design simulation software DesignBuilder, taking small buildings in cold areas of China as an example to optimize the cost and energy of buildings. Wang et al. [21] proposed a set three-stage multi-objective optimization method for combining redundancy analysis, gradient lifting decision tree and NSGA-II algorithm. They took cold areas as an example and used EnergyPlus to optimize building energy consumption, cost and thermal environment to determine the impact of various parameters on the performance of different buildings. Bingham et al. [22] proposed a multi-objective optimization model based on genetic algorithm, artificial neural network and TRNSYS for multi-objective optimization of energy consumption, transformation cost and thermal discomfort hours, which greatly shorten the calculation time on the premise of ensuring the correct rate. Summing up the above research, we can see that the multi-objective optimization methods based on various simulation tools have been relatively mature, and different types of genetic algorithms are widely used to solve architectural design optimization problems [6].

Research on energy-saving optimization design goal of window and sunshade equipment

At present, the performance of windows and sunshade equipment is mainly reflected in building energy consumption, visual performance and thermal environment. Many scholars have done some optimization work. Ochoa et al. [23] determined the size of the window in the form of graphic optimization and obtained excellent visual comfort while reducing energy consumption. Harmathy et al. [24] established an optimized building envelope model using multi-criteria optimization method and BIM program to determine the effective window-to-wall ratio and window shape that affect visual performance quality. Lee et al. [25] optimized window types and obtained good energy consumption by using graphic method and regression analysis. Kwon et al. [26], according to the changes of window–wall ratio and direction, developed optimal lath angle control algorithms

for shutters during cooling and heating periods, respectively, to comprehensively consider various variables controlling louvers. The final optimization results reduce cooling energy consumption by 20.7% and heating energy consumption by 12.3%. Zhao et al. [27] made a comprehensive consideration from the aspects of building orientation, window configuration and sunshade system, in order to minimize heating, cooling, lighting energy consumption and uncomfortable time, and to find out the relationship between them. Based on this, the most recommended variable parameters of window shading configuration in four cities in different climatic region. The existing research is mainly focused on the energy consumption performance of buildings, and less consideration is given to indoor uncomfortable hours and sound insulation effect. And most of the studies only consider some parameters, the optimization results are reflected by U value, solar reflectivity and so on. The consideration is not comprehensive and the feasibility is low. And most of the above studies are only aimed at optimizing one climate region, and an optimization method which can be applied to a variety of climate regions is very necessary.

To sum up, this paper aims to follow the relativity principle of building energy saving, propose a window parameter optimization design model considering the three objectives of building energy consumption, visual performance and indoor thermal environment on the existing optimization analysis framework, and consider the sound insulation effect of windows into the optimization process. Integrate EnergyPlus and NSGA-II algorithms, and use Python programming to complete the multi-objective optimization of windows and sunshade equipment. Taking a hypothetical office room building in Chengdu, Beijing and Guangdong as an example, the window design is studied by coupling dynamic energy consumption simulation software and optimization algorithm. In order to obtain the recommended parameters of windows and shading equipment in three cities: hot summer and cold winter region, hot summer and warm winter region and cold region, and the trade-off between energy consumption, visual performance, indoor thermal environment and sound insulation, the effects of window structure parameters on building energy consumption, visual performance, thermal environment and sound insulation performance optimization are studied. The conclusion of this paper can provide effective design opinions for architectural design, especially for non-programming designers, which not only provide a simple and efficient operation method, but also provide the corresponding implementation scheme for stakeholders.

The full text is organized as follows: The second section introduces the optimization structure; the third section describes the objectives and related setting parameters of the optimization case; the fourth section shows the optimization results and discusses them; and the fifth section describes the conclusions and research deficiencies.

Fig. 1 Optimization process
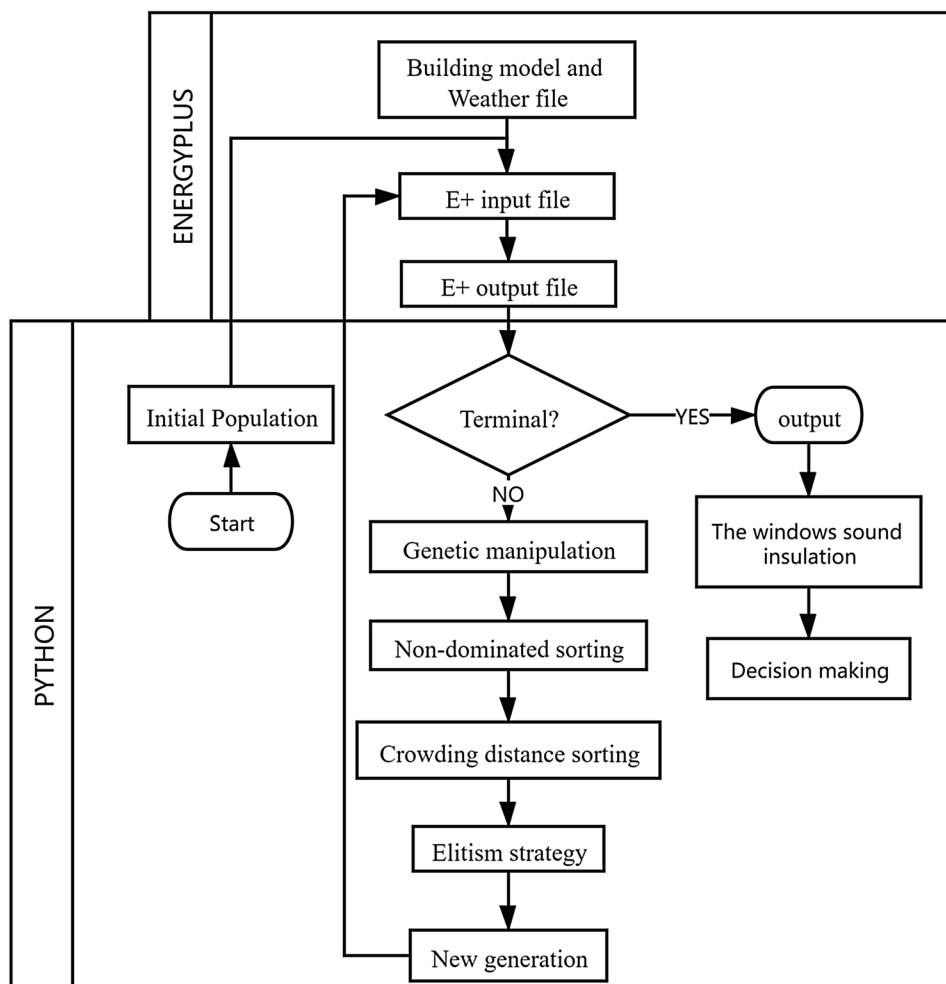
Method

In order to implement the window parameter optimization design based on multi-objective optimization, after defining the optimization problem and objective function, this paper uses the multi-objective optimization method combining NSGA-II and EnergyPlus to optimize window parameters by comprehensively considering building energy consumption, indoor visual performance and indoor thermal environment. As shown in Fig. 1, EnergyPlus is used to model the optimized building, and the values of building energy consumption, visual performance and uncomfortable hours are calculated, the corresponding sound insulation performance is calculated by Python, and the NSGA-II algorithm is written to complete the multi-objective optimization.

Building performance simulation tool

This paper will use the structure which combines the building energy consumption simulation software and optimization tools to optimize. It is a common method of

multi-objective optimization of building energy consumption [22]. The building energy consumption simulation software in this paper will use EnergyPlus to simulate the energy demand of the building. EnergyPlus, prepared jointly by the US Department of Energy and Lawrence Berkeley National Laboratory, can fully simulate the energy performance of dynamic buildings [28]. At the same time, many studies have proved its effectiveness, and the international community has gradually begun to use EnergyPlus as the energy consumption simulation engine of building energy consumption standard [29]. However, the biggest disadvantage of EnergyPlus is its parameterized interface, poor visibility and high difficulty in operation, so OpenStudio [30] has been developed rapidly and widely. It bases on EnergyPlus as the computing kernel and provides a comprehensive and easy-to-operate user interface. At the same time, in order to calculate the building energy consumption, EnergyPlus needs the information of building geometry and thermal area, which can be shared with EnergyPlus in the form of idf file using OpenStudio. The use of OpenStudio can greatly improve

the modeling efficiency of EnergyPlus. So this paper adopts the joint modeling method of OpenStudio and EnergyPlus.

Optimization method

Building performance optimization is usually multi-objective and multi-parameter nonlinear optimization, the properties of different objectives are so different that it is difficult to integrate into one optimization function. In the past few years, many studies have proposed a variety of methods for multi-objective optimization of building energy-saving design, among which the derivative-free optimization method is the most frequently used method for this problem [31]. The algorithms, such as genetic algorithm, particle swarm optimization algorithm, ant colony algorithm and hybrid algorithm, weigh the number of calculations required and the robustness of the optimal solution obtained [32]. Genetic algorithm is the most widely used optimization method.

In this paper, a genetic algorithm with elite retention strategy, that is, non-dominant sorting genetic algorithm (NSGA-II), is used for multi-objective optimization, and the algorithm is realized by Python programming. NSGA-II algorithm is proposed by Srinivas and Deb on the basis of NSGA algorithm in 2000 [33]. The research shows that NSGA-II algorithm has better performance and more convenient calculation. The concept of crowding distance and protection mechanism is put forward, which expands the sampling space and helps to maintain the superiority of the population [34]. Practical research shows that the calculation result of NSGA-II algorithm is also relatively reliable [35], and it is often used as a standard to evaluate other algorithms, so this paper uses NSGA-II algorithm as a multi-objective optimization algorithm. The scenario for coupling NSGA-II with EnergyPlus is shown in Fig. 1. The detailed optimization process is as follows. Firstly, the model needed in this paper is established in Sketchup, and after the model is imported into OpenStudio for parameter setting, the input format file (.idf) of EnergyPlus is exported. And then the supplementary parameter setting of EnergyPlus is used. Python is used to combine EnergyPlus and NSGA-II algorithm, so that it can automatically change the design parameters and read the simulation results according to the algorithm until the optimization standard is reached (Fig. 2).

Case study

In this section, the multi-objective optimization method is applied to a simulated office to optimize the window and shading configuration design.
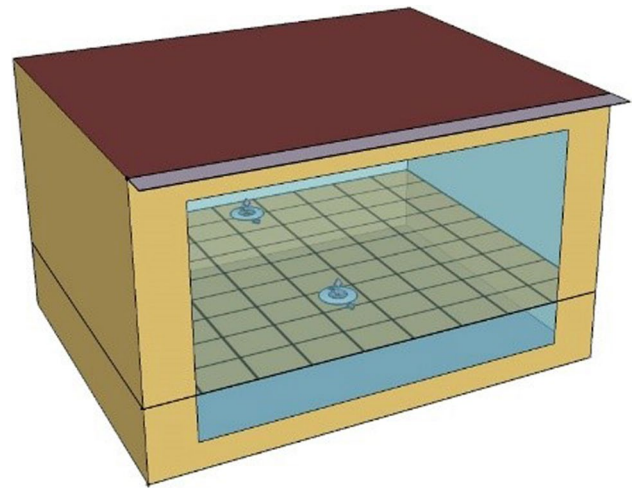

Fig. 2 Test room

Architectural case

Case model

In this paper, a simulated office of $5.0 \times 4.0 \times 3.0$ m is selected, there is only one outer wall, and the rest are inner walls. Set a window at the center of the outer wall. The structure of the exterior wall conforms to the design standards such as "Code for Thermal Design of Civil buildings." Table 1 shows its structure. Except the wall where the window is located is the external wall, the rest of the wall, roof and floor are completely insulated. The sunshade device is arranged above the window, and two automatic dimmers are arranged at the working surface 0.8 m from the ground to control and 10×10 grid. The UDI is calculated, and the dimmer direction is facing the window, as shown in Fig. 3. The input setting parameters are according to the domestic regular working time and the actual situation to set up, as shown in Table 2, and the occupancy rate, lighting and electrical equipment schedule are shown in Fig. 3.

Building climatic region division in China

China is divided into five climatic regions according to the average temperature in the coldest and hottest months of the year, and the days when the daily average temperature is lower than 5 °C and higher than 25 °C [36]. They are cold climate, cold climate, hot summer and cold winter climate, hot summer and warm winter climate and mild climate. This paper takes Chengdu in hot summer and cold winter area, Beijing in cold area and Guangdong as an example to simulate. These cities have good economic development and belong to provincial capitals or municipalities directly under the Central Government. And some scholars have taken
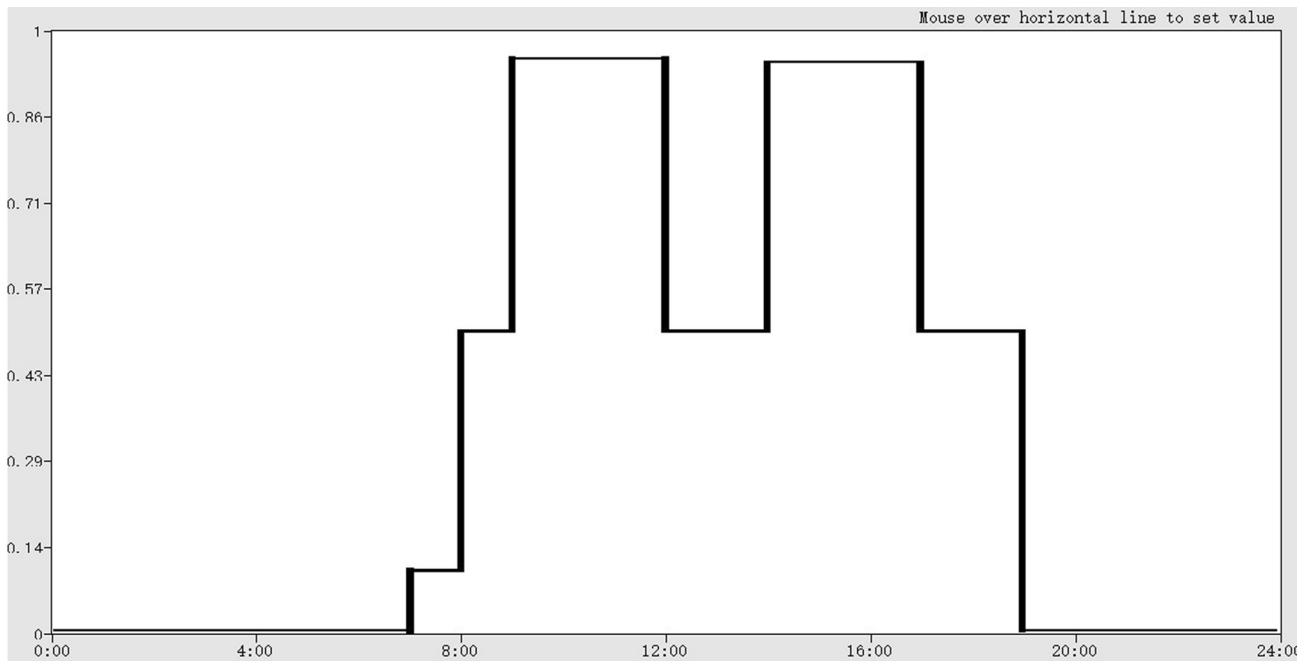
Fig. 3 Personnel occupancy, lighting and electrical equipment schedule

Table 1 Exterior wall structure and heat transfer coefficient

Name of material	Material thickness (mm)	Heat transfer coefficient (W/m^{2}K)
Cement mortar	20	0.59
Extruded polystyrene board	40	
Cement mortar	20	
KP1 brick	200	
Mixed mortar plastering	20	

Table 2 Some initial input setting parameters

Load setting	
Lighting load	2.235 W/m^2
Personnel density	0.06 Person/m^2
Electrical equipment load	5.11 W/m^2
Air-conditioning system setup	
Heating control temperature	20 °C
Refrigeration control temperature	26 °C
Heating/refrigeration start/stop time	Working days 8 a.m.–18 p.m.
Type of air-conditioning system	Ideal air-conditioning system
Climate set	
Climatological area	
	Chengdu, Sichuan
	Beijing, Beijing
	Guangdong, Guangzhou

these cities as examples to carry out related research, which is typical and representative. Therefore, Chengdu, Beijing and Guangdong are selected as the representative cities of the three climatic regions in China, and the other designs of the three cities are the same except for different heating and cooling schedules. The climate data used are obtained from the Chinese standard weather data (CSWD) and simulated with the EnergyPlus 9.0 version.

Climate data

To run the simulation, weather files for three cities are downloaded from the EnergyPlus website and imported into the Grasshopper plug-in in Figs. 4 and 5. As can be seen from the above pictures, there are great differences in temperature distribution and direct sun angle among the three cities. For example, in Beijing, there is little time for the sun to shine directly from the north, the temperature above 26 °C is less than other two regions and below 9 °C is long. In Guangzhou, there is direct sunlight from the north with high
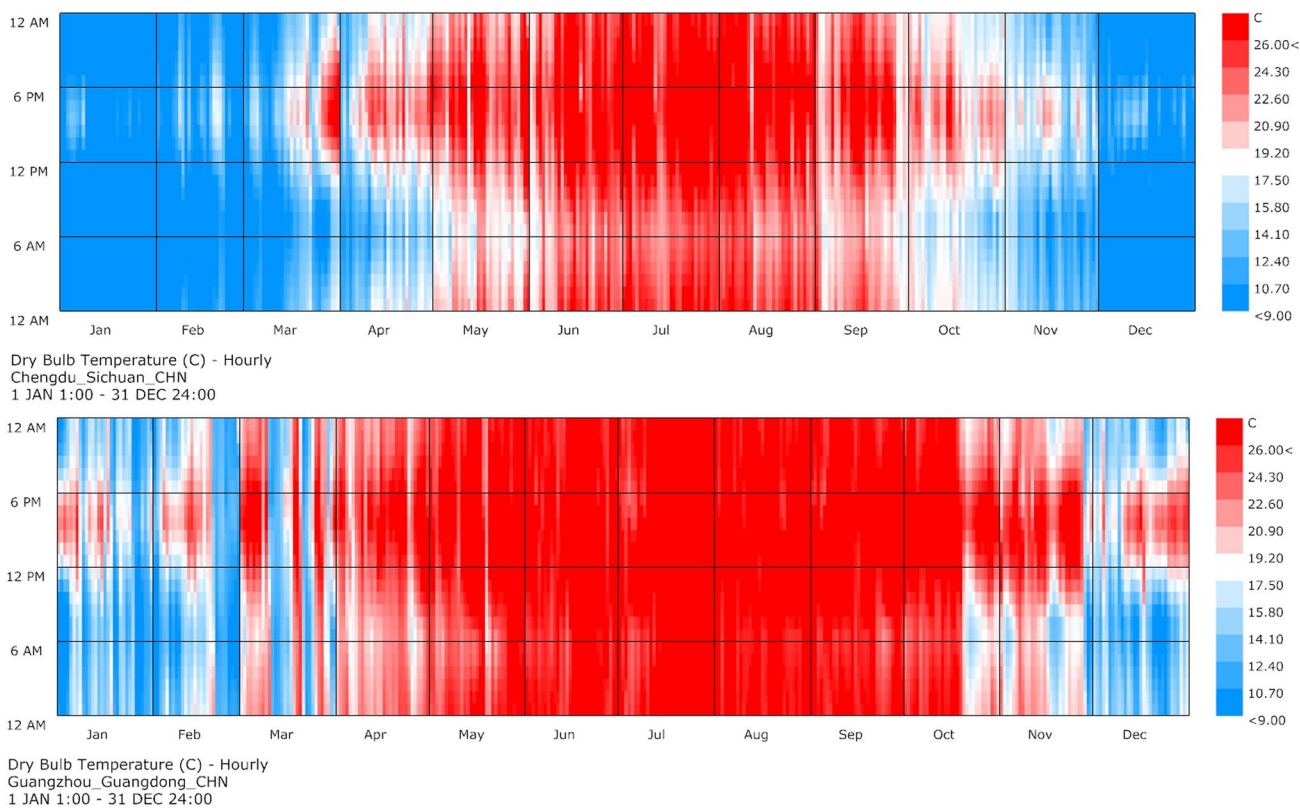
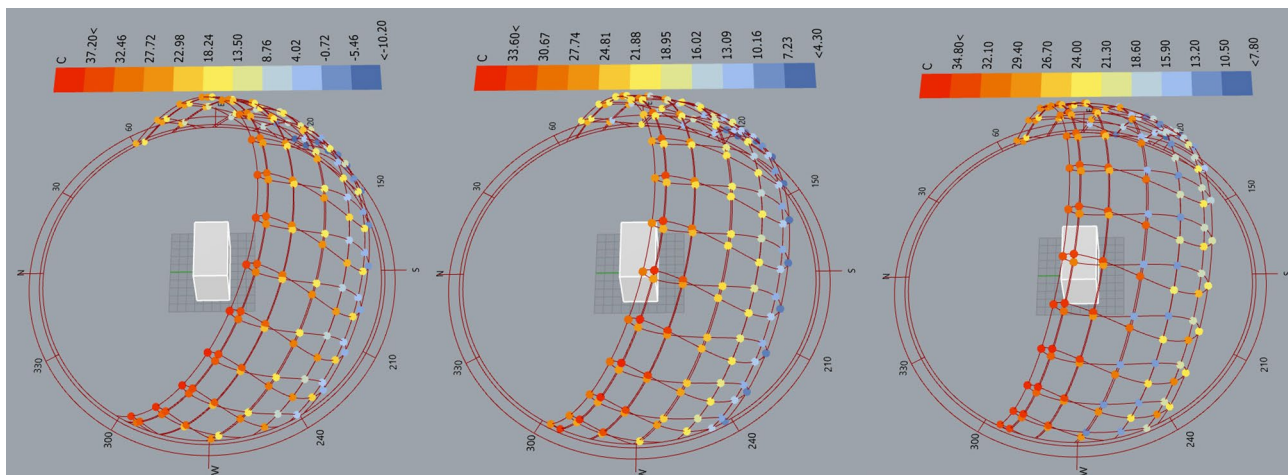**Fig. 4** Dry bulb temperature

Fig. 5 Solar elevation angle and temperature (Beijing, Chengdu, Guangzhou)

temperature and has few time the temperature is lower than 9 °C, which will have a great impact on the design of windows and sunshade systems in different toward. Therefore, in the design stage, it is necessary to pay enough attention to these information to avoid excessive damage to indoor comfort.

Optimization objective function

In this paper, not only the total annual building energy use intensity (EUI), useful daylight illuminance (UDI) and indoor thermal environment (PMV) are analyzed, but also the optimization model considers the building sound insulation (R_r). It is optimized by EnergyPlus simulation and

NSGA-II algorithm. The optimization process is divided into two parts. First, the program obtains the specific values of EUI, UDI and PMV in the optimization process. And then the R_r of the specific values obtained are analyzed and evaluated to obtain effective design information. The optimization objectives EUI, UDI and PMV should be minimized and R_r should be maximized. As shown in formula (1), the above four objective functions that need to be optimized are described in detail below.

$$\min \mathrm{EUI}(x), \mathrm{UDI}(x), \mathrm{PMV}(x)$$
$$\max R_r(x) \tag{1}$$

Total annual building energy use intensity

In order to maintain the air temperature in the room at the set temperature of the air conditioner, it is necessary to add or reduce heat to the air in the room, and the energy consumption in the use phase of the building life cycle accounts for more than 90%. So the building energy consumption in this paper only considers the energy consumption in the use stage. Building energy consumption simulation includes the sum of energy demand for cooling, heating and lighting loads. Energy consumption such as domestic hot water and electronic equipment will not change much in the process of optimization, so it will not be considered. In this case, the "ideal air-conditioning system" (COP=1) is used to study the energy consumption of building air-conditioning. Annual hourly cooling and heating loads are usually used for thermal assessment, and the energy performance indicator in the formula is the annual energy use intensity EUI. EUI is a standardized energy consumption index for the whole building, calculated as shown in the formula (2)–(5).

$$\min \mathrm{EUI} = \mathrm{CEUI} + \mathrm{HEUI} + \mathrm{LEUI} \tag{2}$$

$$\mathrm{CEUI} = \sum_{i=1}^{i=H_c} \mathrm{CEU}_i / S_{\mathrm{CH}} \tag{3}$$

$$\mathrm{HEUI} = \sum_{i=1}^{i=H_h} \mathrm{HEU}_i / S_{\mathrm{CH}} \tag{4}$$

$$\mathrm{LEUI} = \sum_{i=1}^{i=H_l} \mathrm{LEU}_i / S_{\mathrm{L}} \tag{5}$$

CEUI is annual cooling energy consumption intensity; HEUI is annual heating energy consumption intensity; LEUI is annual lighting energy consumption intensity; CEU_i is hourly refrigeration energy consumption demand; HEU_i is hourly heating consumption demand; LEU_i is hourly lighting consumption demand; S_{CH} is the area of refrigeration/heating; and S_{L} is the area of the lighting.

Useful daylight illuminance

UDI refers to the ratio of the number of hours of natural lighting illumination within the useful range of a room in a year to the total number of hours occupied in a year. It shows the useful time ratio of illumination [38]. Its purpose is to identify the required lighting level [37]. Carlucci et al. [39], according to the comprehensive field research data of occupants' behavior, believed that the illumination of UDI within the range of 100-2000lux is more in line with people's use requirements, and the higher the UDI value, the better the visual comfort. In this paper, UDI in this range is used as an evaluation index of visual performance to achieve the requirements of reducing lighting energy consumption and improving visual performance. Therefore, the objective formula of visual performance optimization is described as follows:

$$\mathrm{UDI} = \sum_i (w_i \times t_i)$$
$$w_i = \begin{cases} 1, & \text{if } E_{\mathrm{lower}} \le E_{\mathrm{daylight}} \le E_{\mathrm{upper}} \\ 0, & \text{if } E_{\mathrm{lower}} < E_{\mathrm{daylight}} \cup E_{\mathrm{daylight}} < E_{\mathrm{upper}} \end{cases} \tag{6}$$

t_i is the room occupancy time in a year and w_i is the weight of E_{daylight}.

Indoor thermal environment Fanger PMV

Indoor thermal environment can not only satisfy human body comfort, but also improve people's ability to think and observe. It is of great significance to satisfy and improve indoor thermal environment. In the field of thermal environment research, the research of Fanger et al. [40] is sufficiently representative. The PMV value seven-point scale has been formulated as an international standard. Therefore, this paper uses PMV as the evaluation standard for indoor thermal environment as follows:

$$\mathrm{PMV} = \sum_i P_i$$
$$p_i = \begin{cases} 1, & \text{if } P_{\mathrm{lower}} \le P_{\mathrm{occ}} \le P_{\mathrm{upper}} \\ 0, & \text{if } P_{\mathrm{lower}} < P_{\mathrm{occ}} \cup P_{\mathrm{occ}} < P_{\mathrm{upper}} \end{cases} \tag{7}$$

Window sound insulation effect

Building sound insulation calculation usually has the formula method and computer simulation method. In order to simplify the calculation, this paper adopts the empirical formula method to optimize the sound insulation of buildings. Since exterior walls are generally better than windows for

sound insulation, only windows are optimized. The following formula is generally used in actual engineering [41]:

$$R = 13.5 \times \log m + 13$$
$$R = 13.5 \times \log (m_1 + m_2) + 13 + \triangle R_1 \tag{8}$$

Among them, R is the sound insulation of the window, m is the surface density of the component, m_1 and m_2 are the surface density of the component members, and $\triangle R_1$ is the additional sound insulation of the middle layer. The International Organization for standardization also recommends the calculation method of the required single-value sound insulation. In summary, the calculation of the window sound insulation effect is shown in formula (9):

$$\max R_r = N_0 - N_1 + 10 \times \log T_0 + 10 \log \frac{S}{V} + 11 \tag{9}$$

Among them, N_0 is the outdoor noise level, N_1 is the allowable indoor sound level, T_0 is the indoor reverberation time, S is the window area, and V is the indoor room volume. In order to meet the requirements of relevant national regulations for sound insulation, this paper calculates the sound insulation of windows on the window-opening side envelope structure. According to [42], the allowable noise level of high-demand offices is 35 dB or less, so $N_1 = 35$ in the formula. It is stipulated in [43] that the standard value of environmental noise on both sides of the main traffic line is 70 dB, so this paper intends to adopt $N_0 = 70$.

Optimization parameters

The building orientation has a great influence on the window design. The different orientation will make the room receive different solar illuminance and radiation intensity, which will affect the choice of window materials. In order to make the research more comprehensive, it is necessary to examine the windows with different orientation. Configure to study, glass is the largest component of the window area,

and its material characteristics have an important impact on the performance of the window system. Compared with the window system optimization method through the window U value, the use of different window materials as optimization parameters has better practicality. Therefore, when optimizing the case building, the window parameters were changed according to the value range shown in Table 3. In the table, CLEAR means glass without any impurities; LoE is low-e glass; BRONZE, GREY, GREEN and LOWIRON are glass with specified colors. The specific properties of each glass are obtained from "WindowGlassMaterials.idf" in the file provided by EnergyPlus, and the specific parameters of the air layer filling gas are provided by "WindowGasMaterials.idf." Considering the available options for each design, Table 3 shows that each parameter type is discrete. When a single-layer window is selected, the coding position of the air layer type and the inner glass type is meaningless.

Algorithm parameter setting

The parameter settings of the NSGA-II algorithm generally include population size, crossover rate, mutation rate and maximum evolution algebra. These parameters play a vital role in the final optimization result, and the setting of various parameters for different optimization problems is not exact. The decisive effect on the convergence of the algorithm is the crossover and mutation operations [44]. The purpose of crossover is to generate new gene combinations. A larger crossover rate can make the hybridization of each generation complete, but the probability of damage to good individuals will increase. , A small crossover rate may lead to slow evolution, usually 0.5–1 crossover rate [45]. Mutation operation can prevent the optimization process from prematurely converging in the immature area, and can repair and supplement the genes that may be lost in the crossover operation. When the mutation rate is large, it can increase the diversity of the population, but it may damage the excellent individuals. Immature convergence, the value range is generally

Table 3 Window parameter value

Window parameters	Range of values
Toward	East/west/south/north
WWR	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Glass layers	1,2
Window outside layer material	CLEAR 3MM, CLEAR 6MM, CLEAR 12MM, BRONZE 6MM, BRONZE 10MM, GREY 6MM, GREY 12MM, GREEN 6MM, LOW IRON 5MM, BLUE 6MM, LoE CLEAR 3MM, LoE CLEAR 6MM
Window medium layer material	AIR 3MM, AIR 6MM, AIR 8MM, AIR 13MM, ARGON 3MM, ARGON 6MM, ARGON 8MM, ARGON 13MM
Window inside layer material	CLEAR 3MM, CLEAR 6MM, CLEAR 12MM, BRONZE 6MM, BRONZE 10MM, GREY 6MM, GREY 12MM, GREEN 6MM, LOW IRON 5MM, BLUE 6MM
Overhangs installation angle	30°, 60°, 90°, 120°, 150°
Overhangs depth	0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, 0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.0 m

0.0001–0.2 [46]. The population size and number of iterations will affect the calculation speed and convergence of the algorithm. Too large will make the calculation time too long and reduce the calculation efficiency. Too small may lead to local convergence. Some studies have shown that the population size is only 2–6 times of the number of design variables, and the number of iterations is usually set to 50 times [47]. According to the above discussion, the algorithm parameter settings are shown in Table 4. When the algorithm reaches the maximum evolution algebra, the calculation is terminated. Therefore, there are a total of 3,456,000 design schemes. Each EnergyPlus simulation takes about 10 seconds, and a detailed calculation takes about 400 days. According to the NSGA-II algorithm shown in the previous section, it saves 99% of time compared to the exhaustive method.

Results and analysis

2D result analysis

This paper solves a three-objective optimization problem. After 50 iterations, the optimization results have converged. In order to more intuitively understand the relationship between the two targets in each area and direction, the configuration of each window and shading configuration is shown in Figs. 6, 7, 8, 9, 10 and 11. Each point in the figure represents one design solution of a window, and the red point represents the Pareto optimal solution. It can be observed in the figure that the objective functions are in conflict with each other. When one objective reaches the optimum, the other objectives often fail to reach the optimum. Except for the window opening in the south direction of Beijing, the change trend of the objective function in each direction of the three climate zones is similar. It indicates that the three objective functions influence each other through a certain coupling relationship. In "Detailed optimization result analysis" section, the different causes of the results are analyzed. At the same time, due to the conflict between the objective functions, the Pareto solution set of the two-dimensional view is not completely distributed on the boundary of the region.

By comparing the Pareto optimal solutions for all orientation between cities in the three climate zones, we can observe that the relationship between the three of

Guangzhou is relatively clear, followed by Chengdu. And the relationship in Beijing is relatively vague. This may be due to Beijing's location, whose climatic zone is more complex. The four seasons are far more different. Different window and shading configuration configurations are affected by the weather. It leads to an unclear relationship with the final results.

For the relationship between the two of the three objectives, after observing the design solution and Pareto optimal solution of different orientations of (a) diagram in each climatic zone, we can see that the changing trend of southward window is different from that of the other three directions. In the east, west and north directions, the indoor thermal discomfort decreases first and then increases with the increase in the energy consumption, while the decreasing trend in the south is not obvious. This is because with the increase in WWR, the room can get more solar heat, which is conducive to raising the indoor temperature in winter, but at the same time, it will cause indoor overheating in summer. A reasonable WWR makes it easier to control the indoor temperature within the comfort range. Too small may make people more likely to feel cold, and if too large, the probability of overheating will increase. Because the intensity of solar radiation in the south side of the window is stronger than that in other directions, the smaller WWR can obtain the solar radiation heat obtained in the case of larger WWR in other directions, so the decreasing trend of the front segment of the south side window is reduced.

The analysis of the (b) diagram in all directions in Figs. 6, 7, 8, 9, 10 and 11 shows that when the energy consumption increases in the current year, the proportion of UDI in the set range will increase. It indicates that more energy needs to be consumed in order to achieve better visual effects. The reason for this is that the larger the WWR, the easier it is to get good indoor visual effects. With the increase in WWR, the solar radiation increases and the U value of the outer structure decreases, which increases the energy consumption. At the same time, when the WWR increases to a certain extent, the improvement of indoor visual effect is no longer obvious and the energy consumption continues to increase, indicating that too large WWR is not only not conducive to energy consumption control but also easy to cause glare, so that the indoor UDI is too large, beyond the set range of UDI. The relationship between indoor thermal environment and indoor visual effect is shown in (c). In Pareto concentration, with the improvement of indoor visual effect, indoor thermal discomfort decreases at first and then increases, which is also due to the joint influence of WWR and solar radiation intensity.

As shown in Figs. 6, 7 and 8, 9, the energy consumption of Pareto disassembly with southward windowing in cold regions and hot summer and cold winter regions is relatively narrow. More over the maximum energy consumption of

Table 4 Parameter settings in NSGA-II

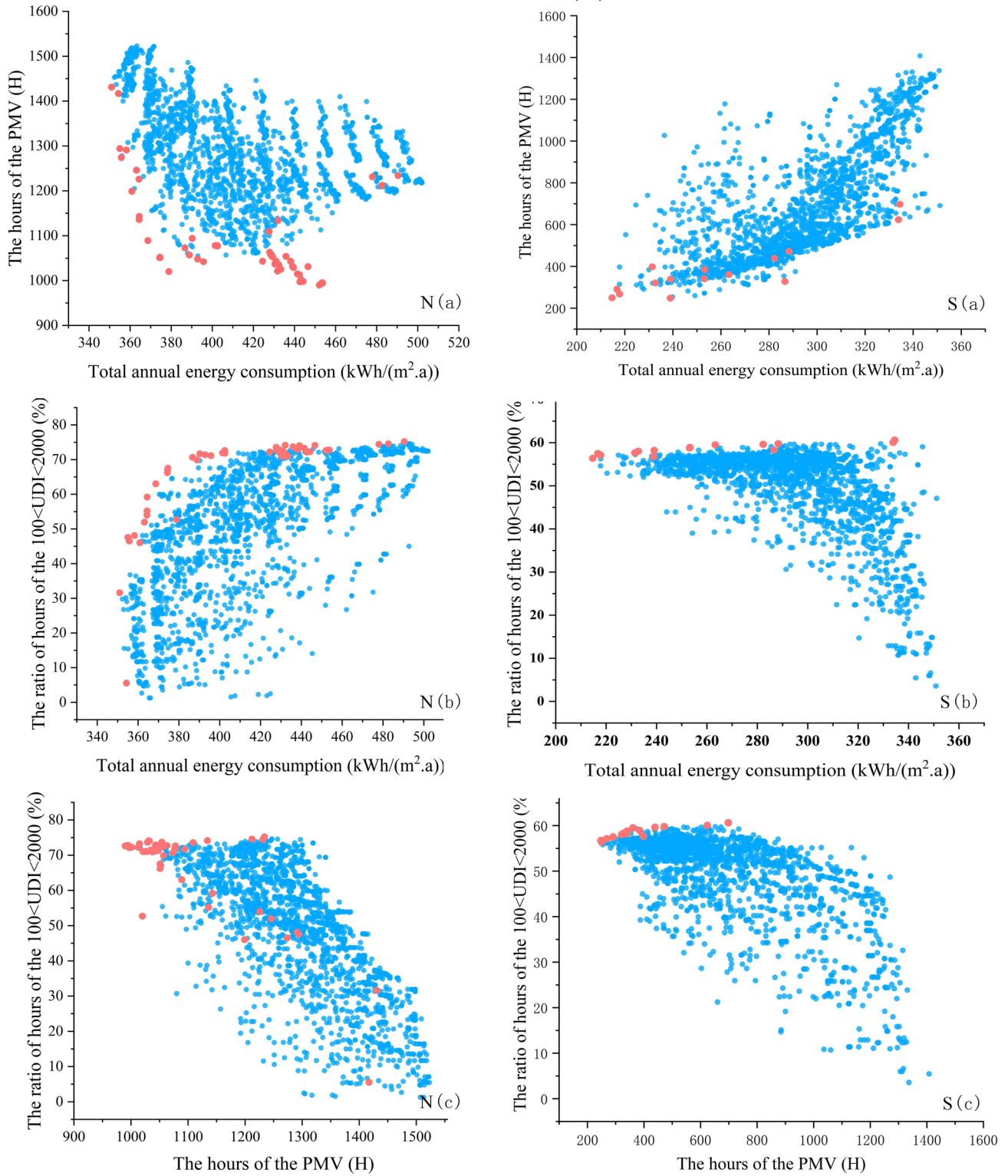| Population size	Cross rate	Variance rate	Maximum evolutionary algebra
32	1.0	0.2	50

BEIJING (a)

Fig. 6 Each of two objectives optimization results in Beijing(a)
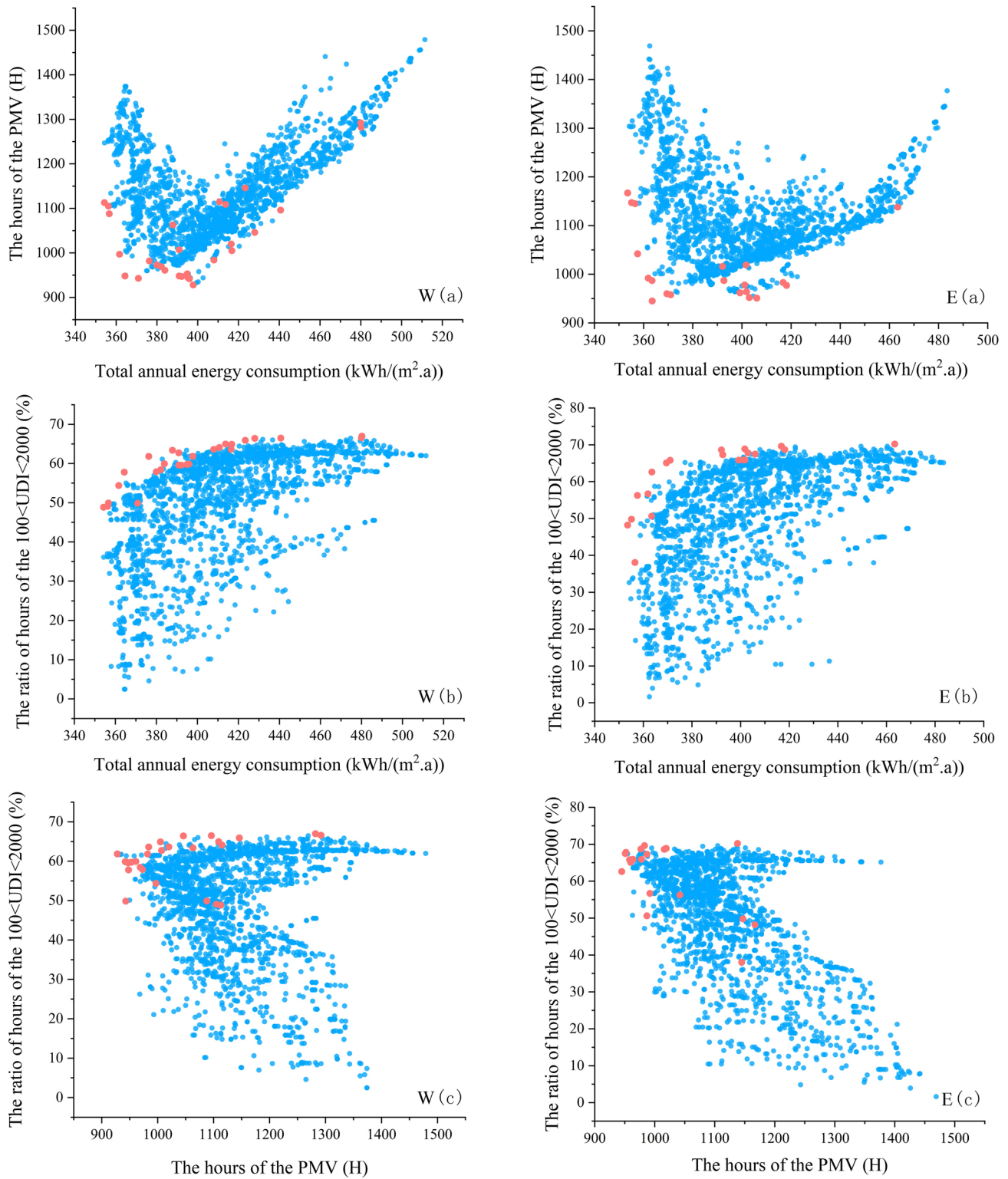
BEIJING (b)

Fig. 7 Each of two objectives optimization results in Beijing(b)
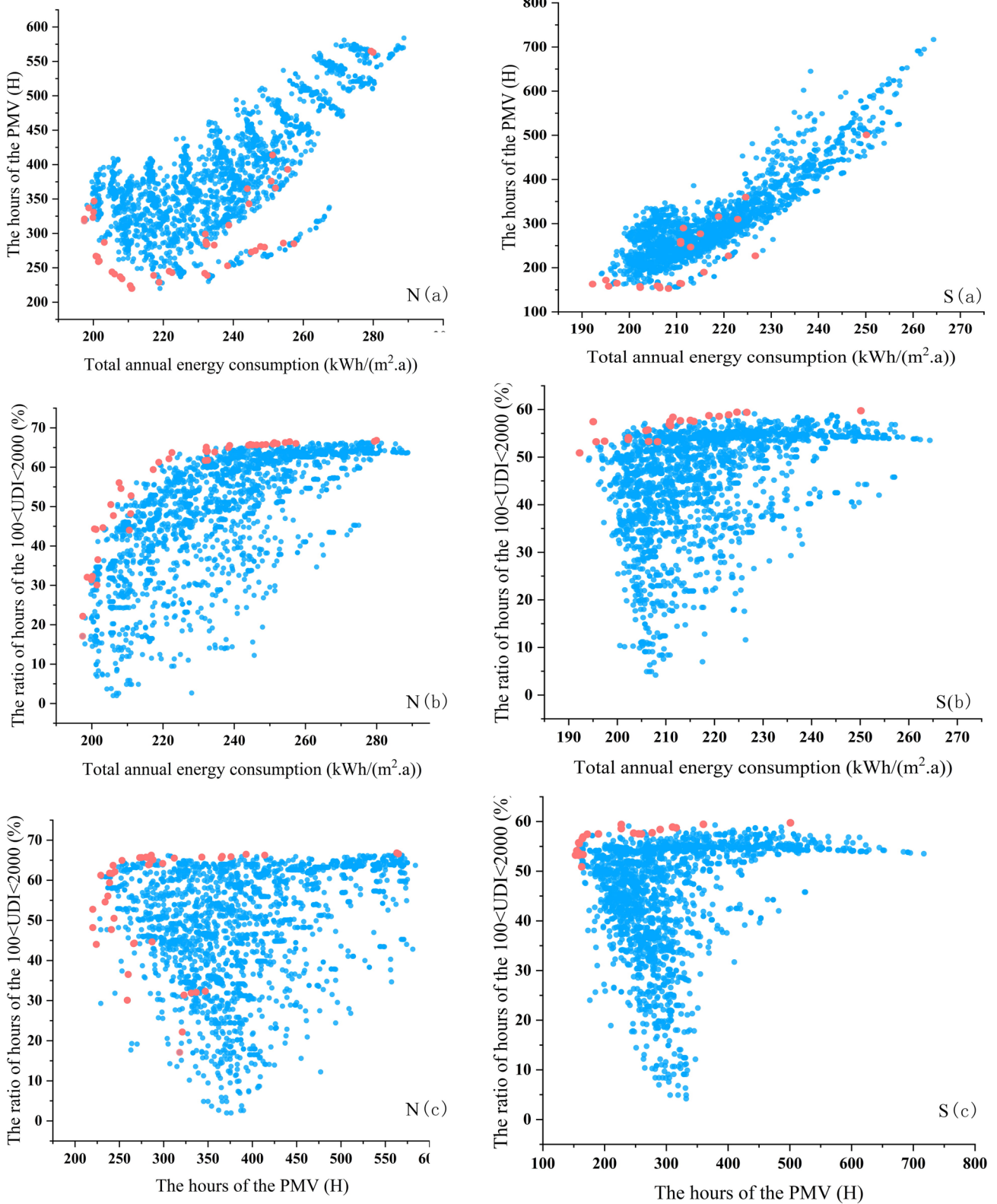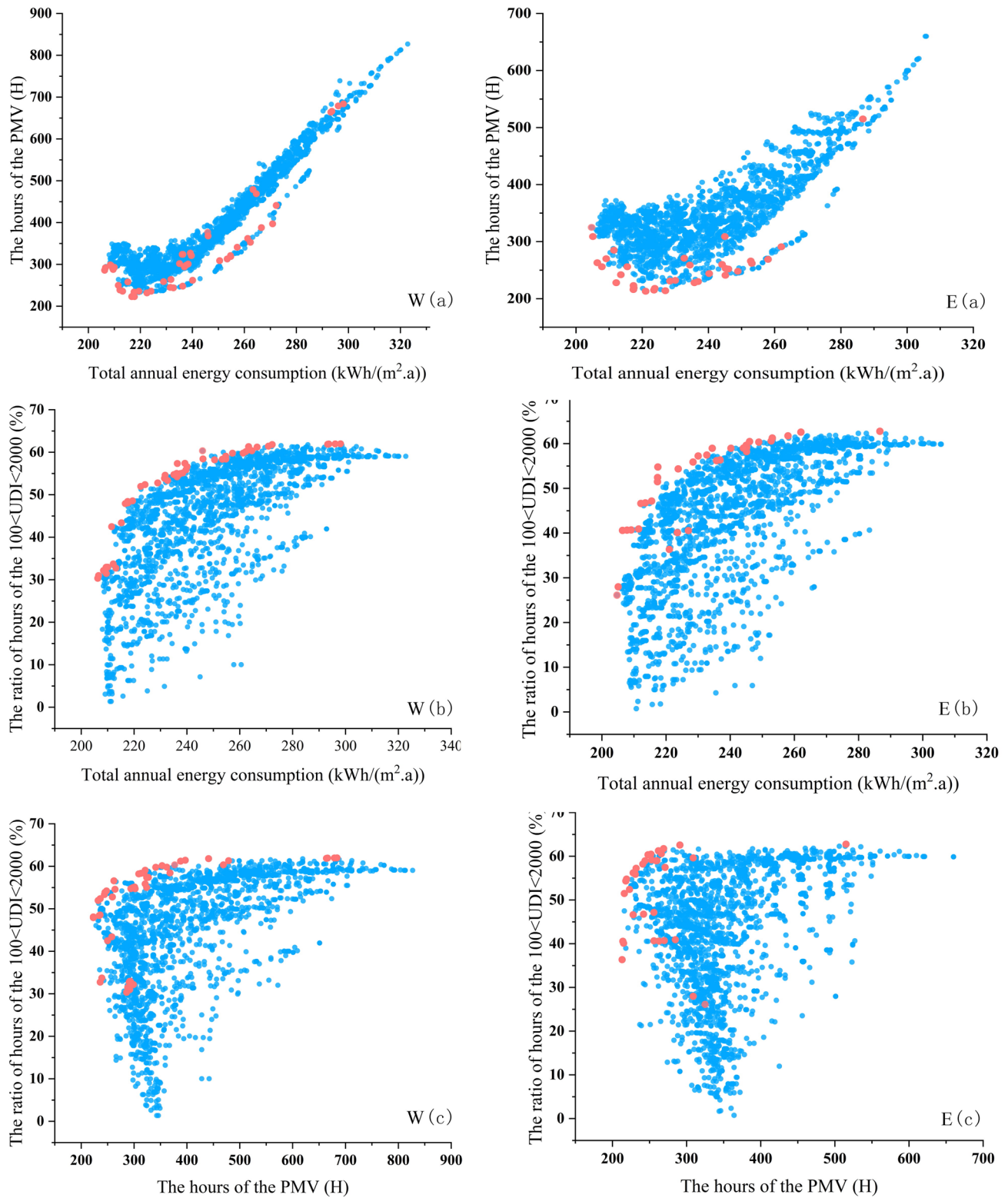
CHENGDU(a)

Fig. 8 Each of two objectives optimization results in Chengdu(a)

CHENGDU (b)

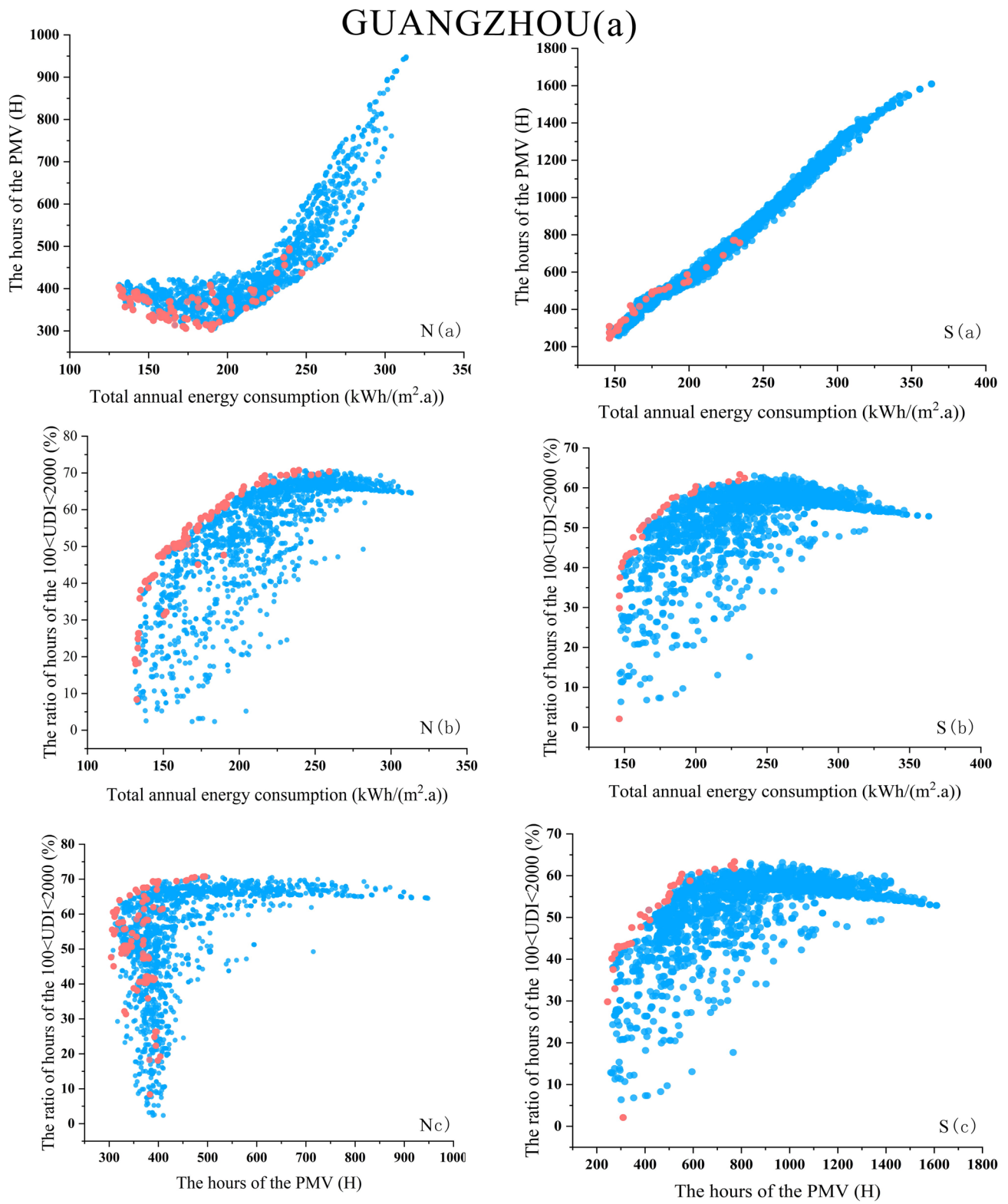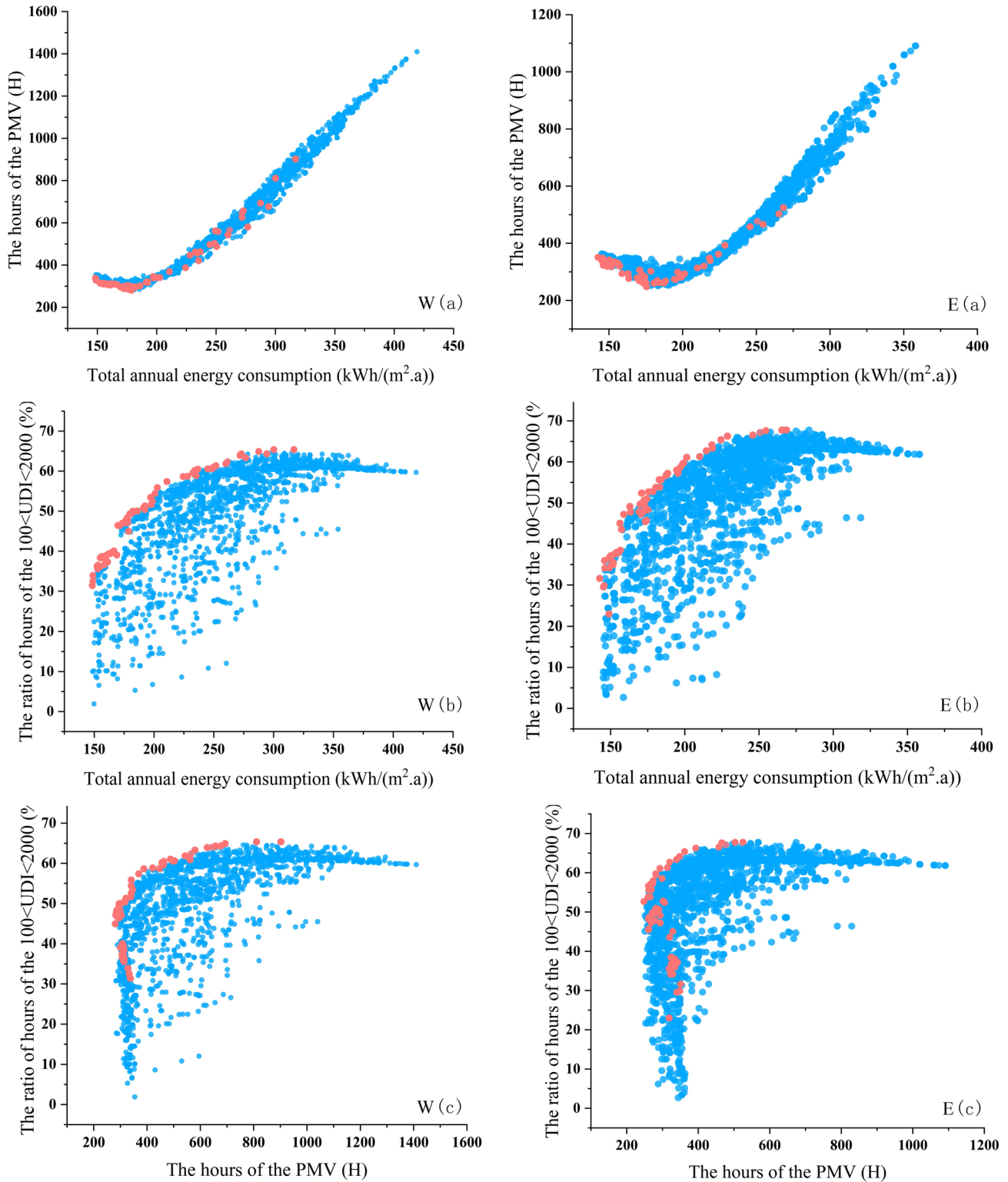**Fig. 9** Each of two objectives optimization results in Chengdu(b)

Fig. 10 Each of two objectives optimization results in Guangzhou(a)

GUANGHZHOU (b)

Fig. 11 Each of two objectives optimization results in Guangzhou(b)

disassembly is lower than that of the other three directions. This may be due to the fact that southward rooms gain more solar radiation heating gain in winter, thus reducing heating energy consumption. Guangzhou in Figs. 10 and 11 is in a hot summer and winter heating area, which does not need to heat in winter. Through the control of the window and sunshade system, the maximum energy consumption of the south side is similar to that of the north side and the east side. The energy consumption of westward window is higher in these climatic zones, especially in Chengdu and Guangzhou. The reason is that excessive heat from westward windows in summer leads to the increase in refrigeration energy consumption, which leads to the increase in the overall energy consumption. Due to the cold winter in Beijing, opening windows on the north side is not conducive to obtaining solar radiation in winter, so the energy consumption of heating in winter increases, which leads to the increase in the energy consumption of windowed rooms on the north side. Therefore, for hot summer and cold winter areas and hot summer and warm winter areas, more attention should be paid to the design of windows on the west side, and reasonable optimization should be made for the windows on the north side and west side of the cold areas.

It can also be seen that the Pareto solutions in Beijing are relatively loose compared with Chengdu and Guangzhou. And the PMV of each optimization result is quite different. The variation range of PMV in Guangzhou and Chengdu is about 300h, but that of Beijing PMV is about 500h and scattered. It indicates that the fluctuation range of uncomfortable hours in cold areas is larger, while that in hot summer and cold winter areas and hot summer and warm winter areas is smaller. Therefore, when optimizing the design of windows and sunshade systems in cold areas, we need to pay more attention to the changes of PMV.

3D result analysis

In order to better show and analyze the distribution of the Pareto solution set of the three objective functions and the trend and the reason of the change, the (a) in Figs. 12, 13, 14, 15, 16 and 17 shows the relationship between the Pareto solution set and the number of window layers. (b) is the corresponding relationship between the solution set and the sound insulation effect. The color mapping of (c) is WWR.

In the (a) of Fig. 12, 13, 14, 15, 16 and17, it can be concluded that single-layer glass is more favorable for daylighting than double-layer glass. At the same time, it will produce a solution with a higher upper limit of energy consumption and a lower limit of comfort hours than double-layer glass. But this does not mean that only the optimization of double-layer windows can be considered in the design. Taking the N(a) of Figs. 14 and 15 as an example, the solution set A is single layer and the solution B is double layer, and

the energy consumption level between the two is similar. However, the comfort and visual performance of the single-layer window system are better than those of the double-layer glass window system. Although the U value of the single-layer window is higher than that of the double-glazed window of the same area, the single-layer window has higher light transmittance and better visual performance effect under smaller WWR. So a better Pareto solution may be produced by reasonably optimizing the window and sunshade system.

In the (b) of the above three figures, we can see that there is no obvious relationship between the sound insulation effect of the window system and the three goals. But with the increase in WWR, the sound insulation level decreases as a whole. And the number of solutions that do not meet the requirements is also increasing. The sound insulation effect of single-layer windows is weaker than that of double-layer windows of the same size, so the use of single-story windows can be considered for buildings with low requirements for sound insulation or in quiet areas. But the more demanding rooms can no longer consider the larger single-story windows of WWR.

Through the analysis of (c), it can be found that the indoor visual effect continues to improve with the increase in WWR in the three climatic regions. But when it increases to a certain extent, the improvement of visual effect is no longer obvious, while the indoor energy consumption and uncomfortable hours will increase significantly. The reason is explained in "2D result analysis" section, so it is not recommended to use excessive WWR window system when there is no high requirement for indoor visual effect.

Detailed optimization result analysis

Figures 18, 19, 20, 21, 22 and 23 show the distribution frequency of Pareto solution set design variables for windows and shading configuration in all directions in three cities. Through these Pareto solution sets, we can see that the recommended parameters of some optimization variables are roughly the same while some are completely different, which are analyzed in detail as follows. For the choice of single- and double-layer windows, even in the same climate zone, the recommended number of layers is different in different directions. For example, in Beijing area, there are more optimization schemes for single layer in the north and west, and more double layer in the south and east. And the WWR of the Pareto solution of the single-layer window system is mostly larger than 0.5. This may be because single-layer windows are easier to obtain the advantage of better indoor visual comfort. Single-layer windows' indoor visual comfort can be further improved, so smaller WWR can be used in similar visual comfort to obtain similar or lower energy consumption and uncomfortable hours than double-layer

Fig. 12 Each of three objectives optimization results in Beijing(a)
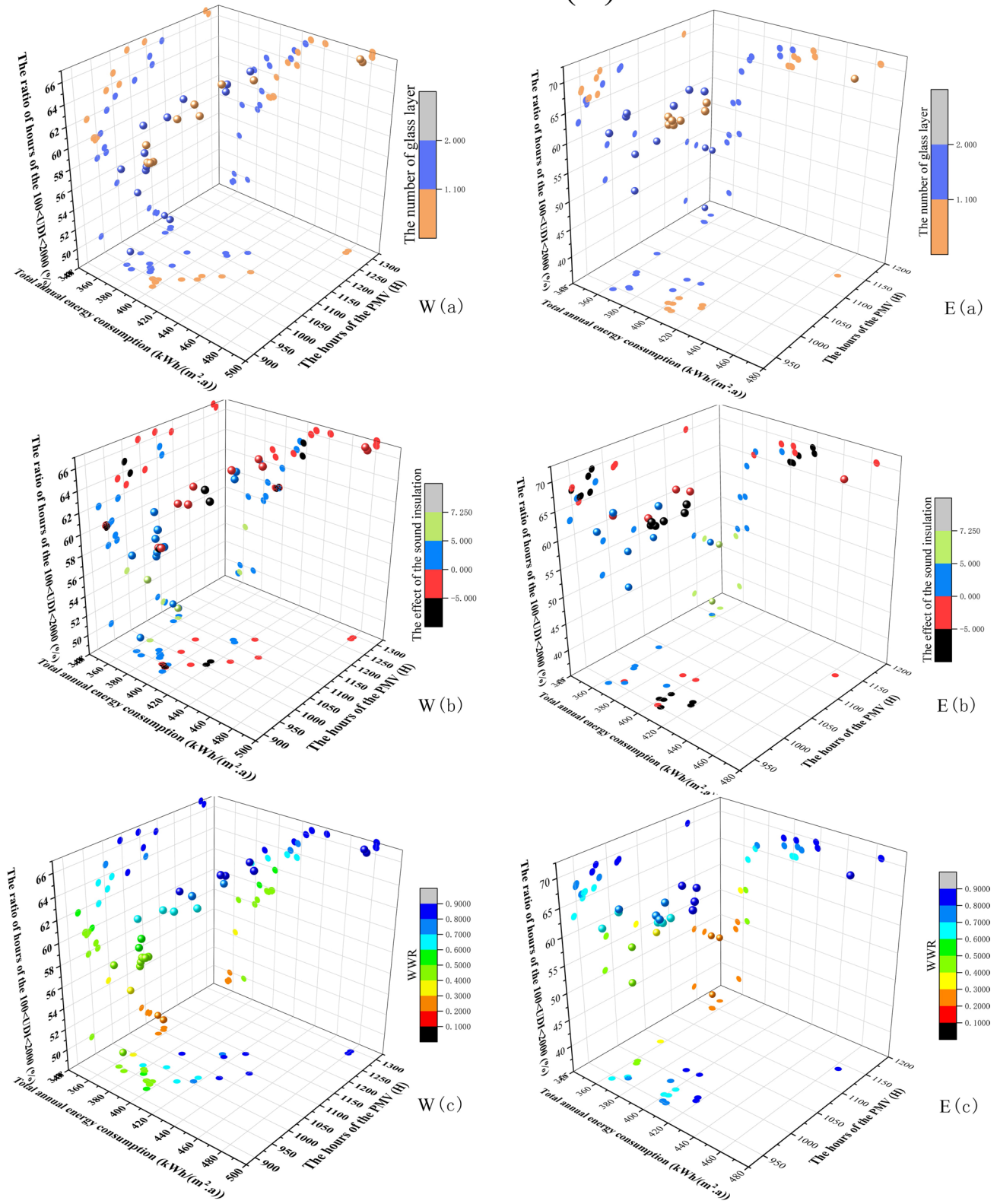
BEIJING (B)

Fig. 13 Each of three objectives optimization results in Beijing(b)
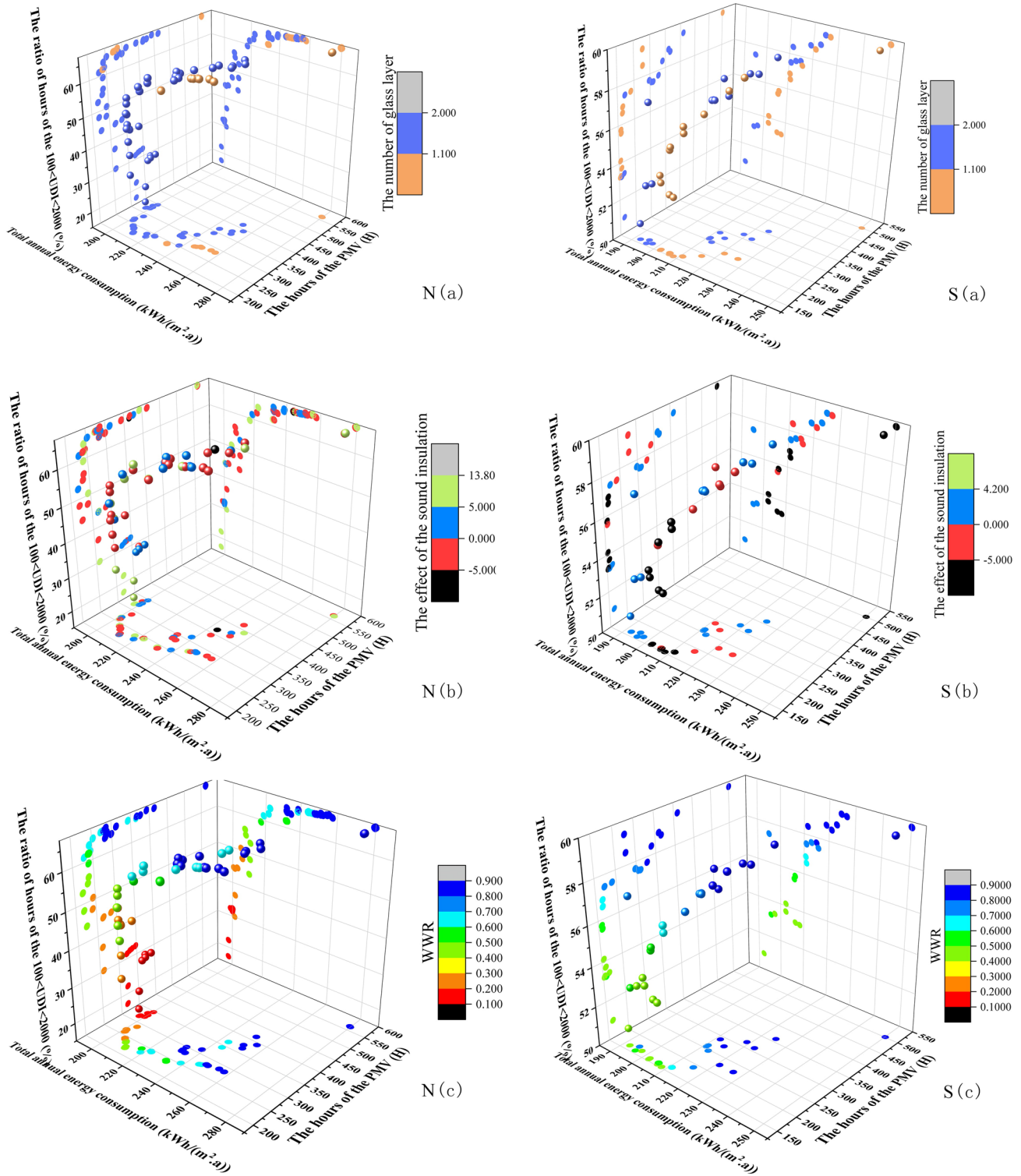
CHENGDU (A)

Fig. 14 Each of three objectives optimization results in Chengdu(a)
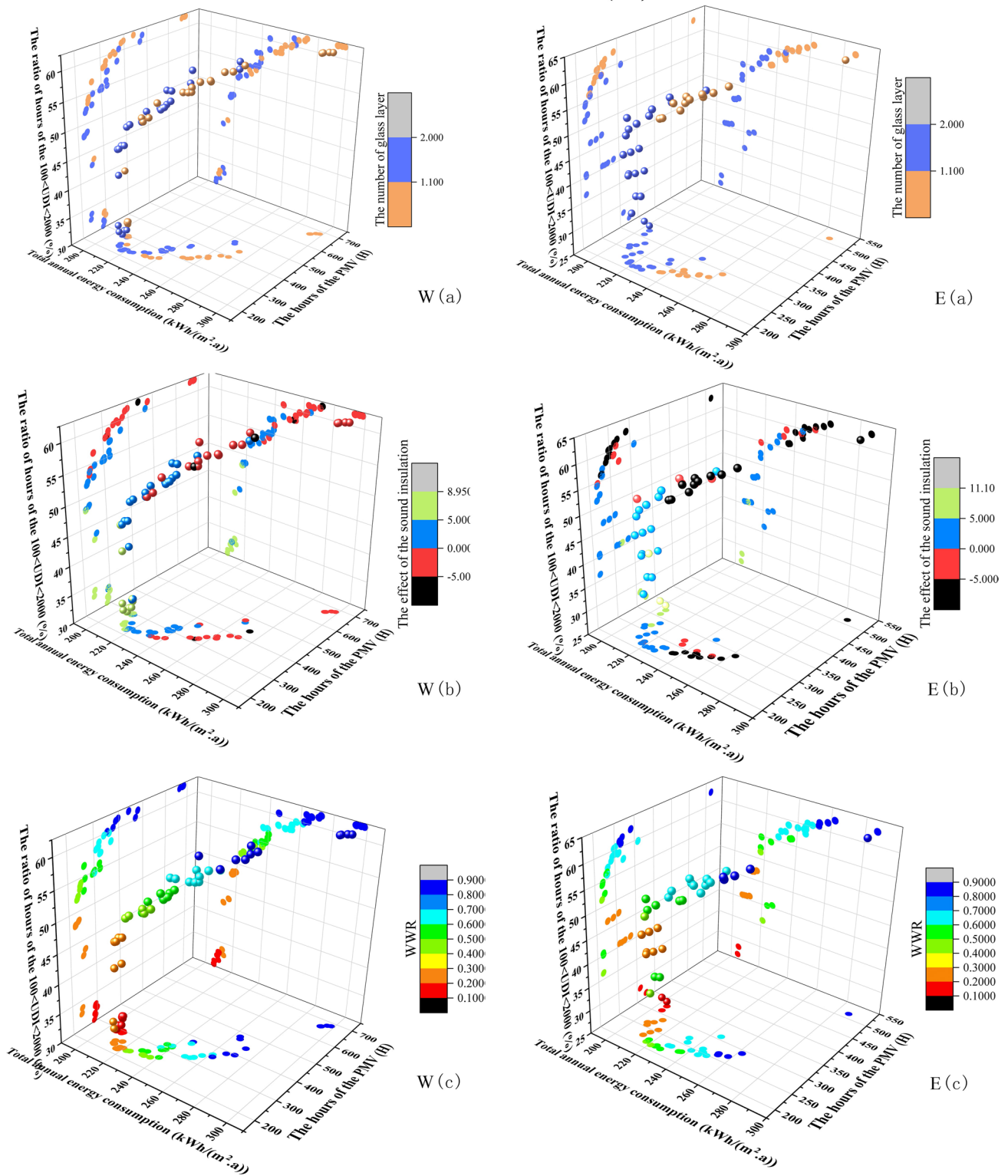
CHENGDU (B)

Fig. 15 Each of three objectives optimization results in Chengdu(b)
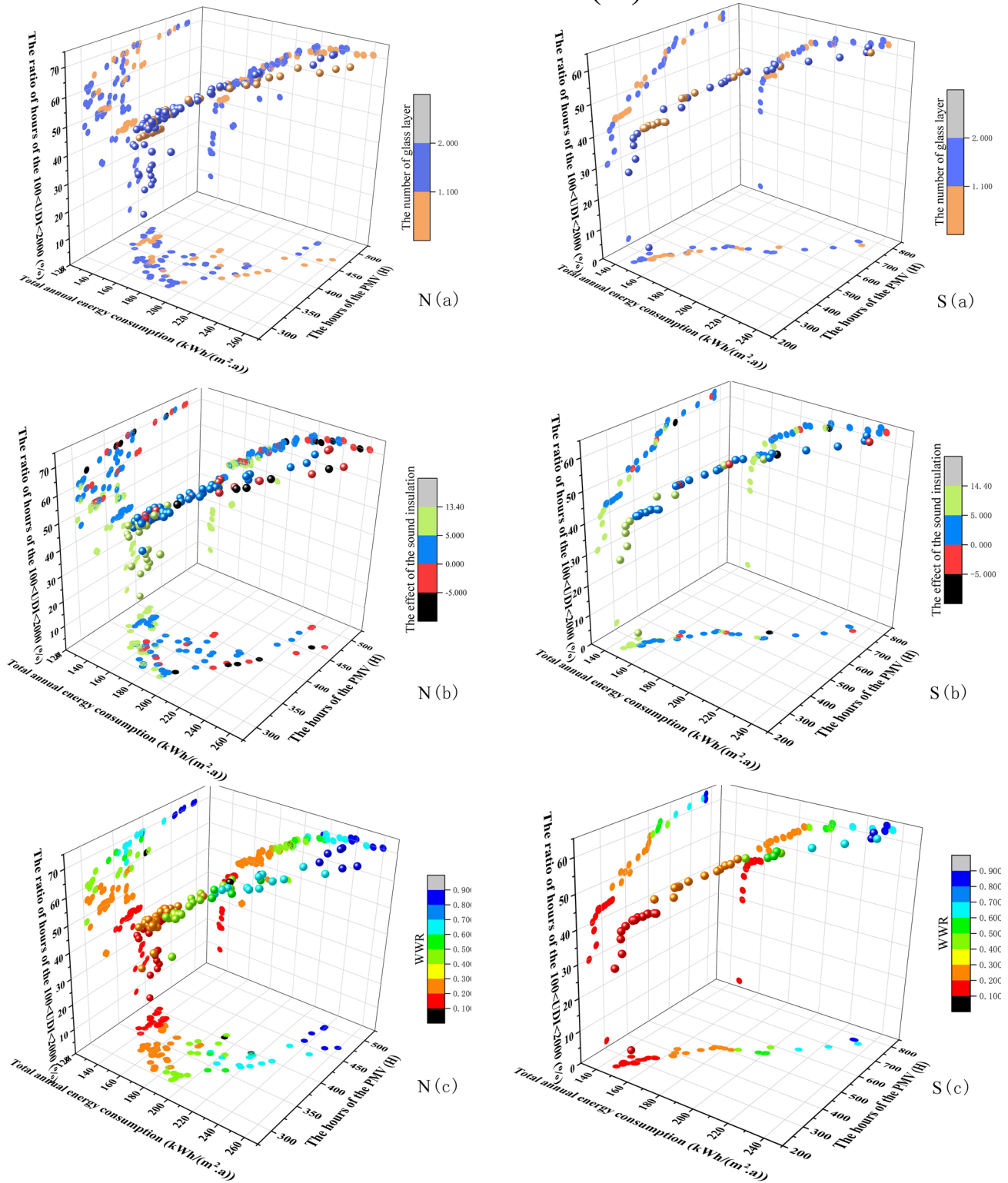
GUANGZHOU (A)

Fig. 16 Each of three objectives optimization results in Guangzhou(a)
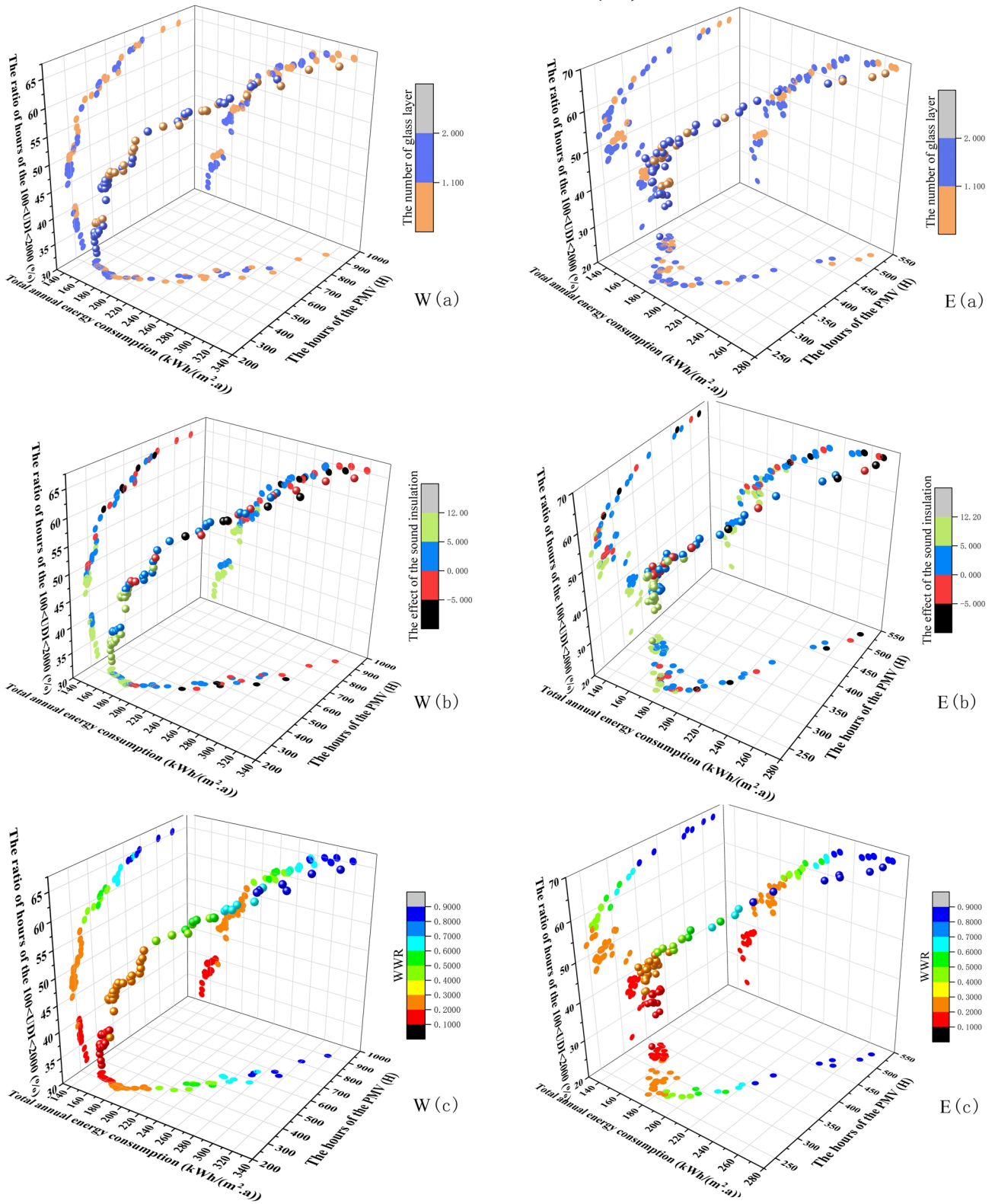
GUANGZHOU (B)

Fig. 17 Each of three objectives optimization results in Guangzhou(b)

Fig. 18 Frequency of variables appearing in the optimization results in Beijing(a)

Fig. 19 Frequency of variables appearing in the optimization results in Beijing(b)

Fig. 20 Frequency of variables appearing in the optimization results in Chengdu(a)

Fig. 21 Frequency of variables appearing in the optimization results in Chengdu(b)
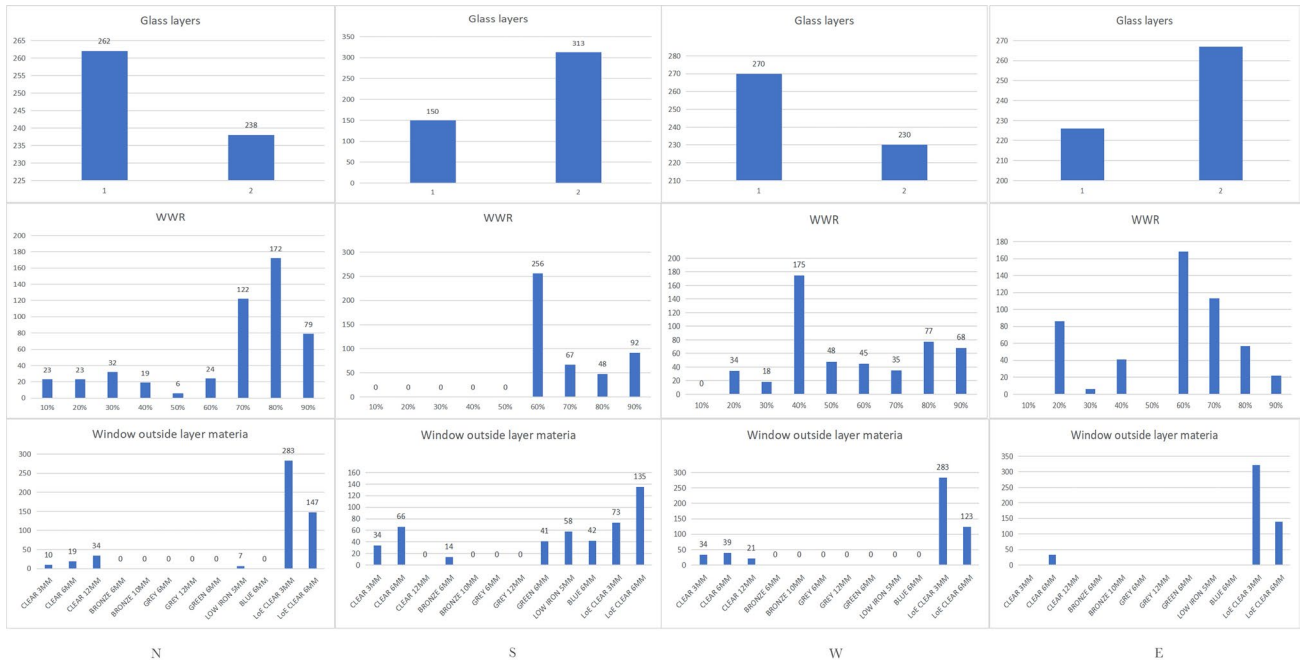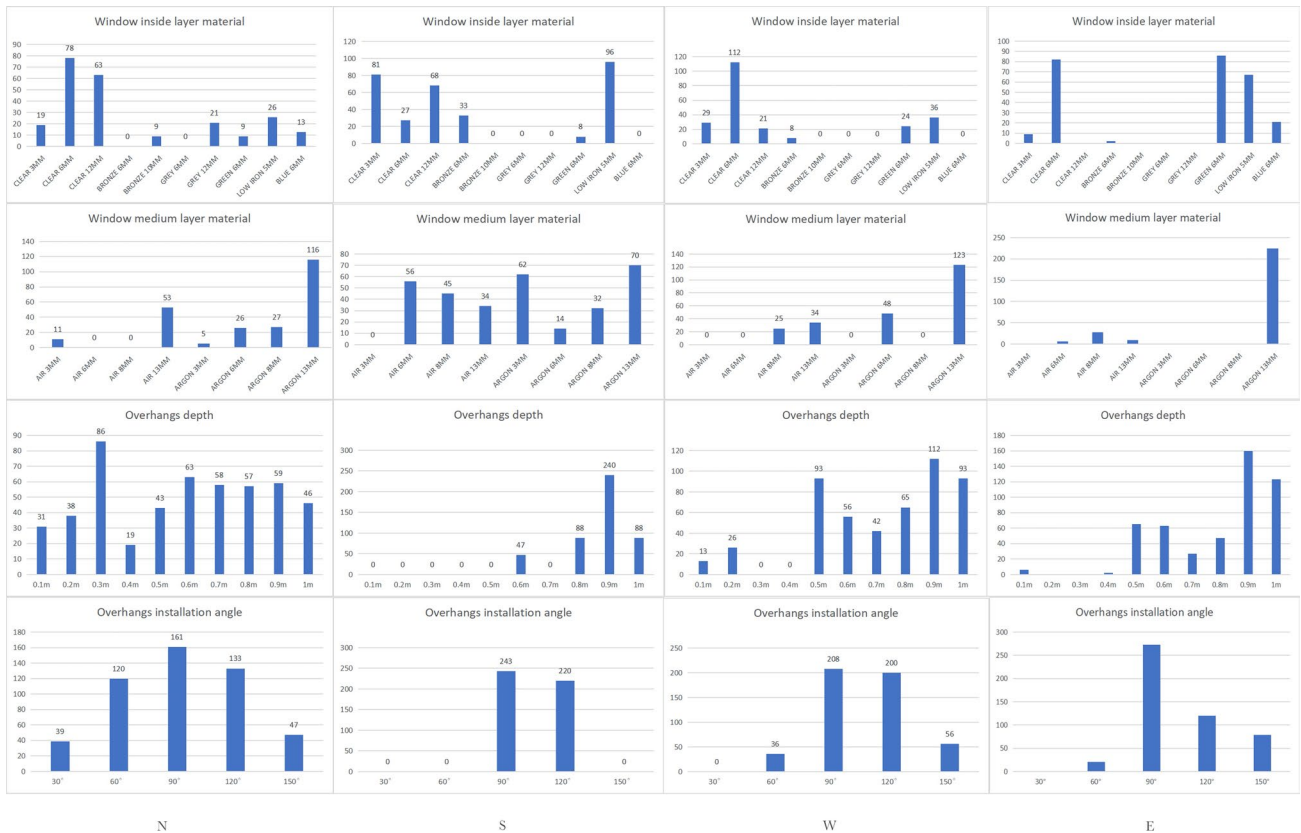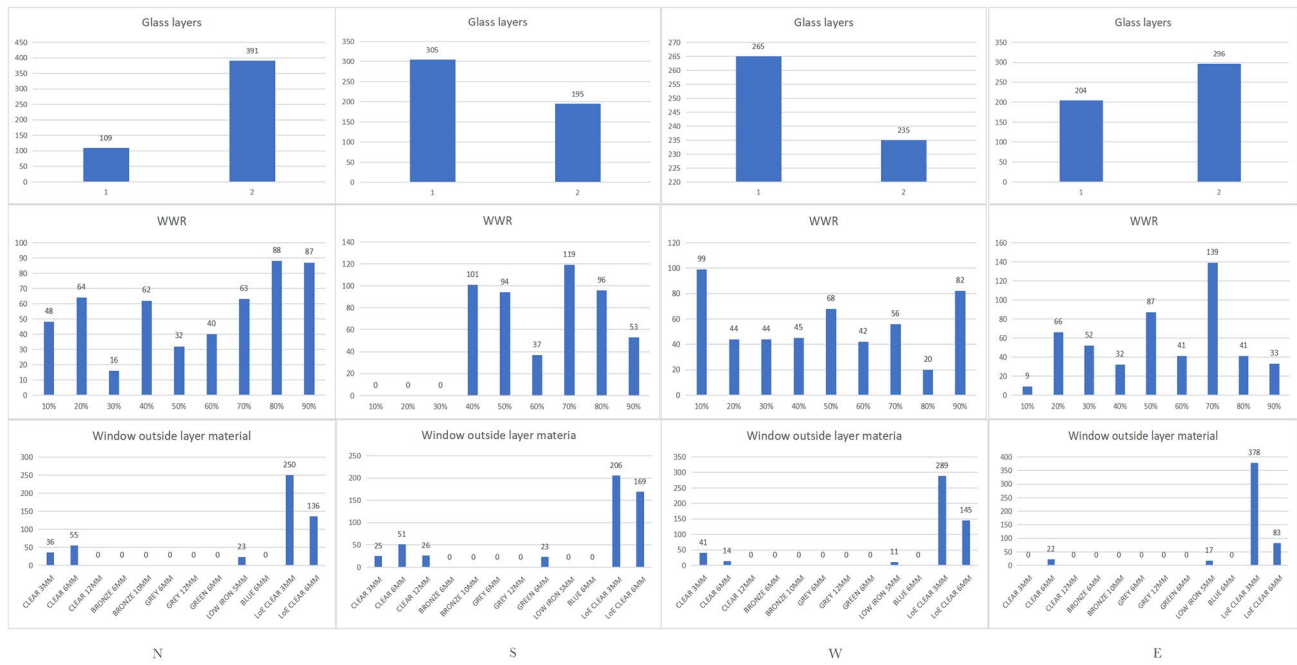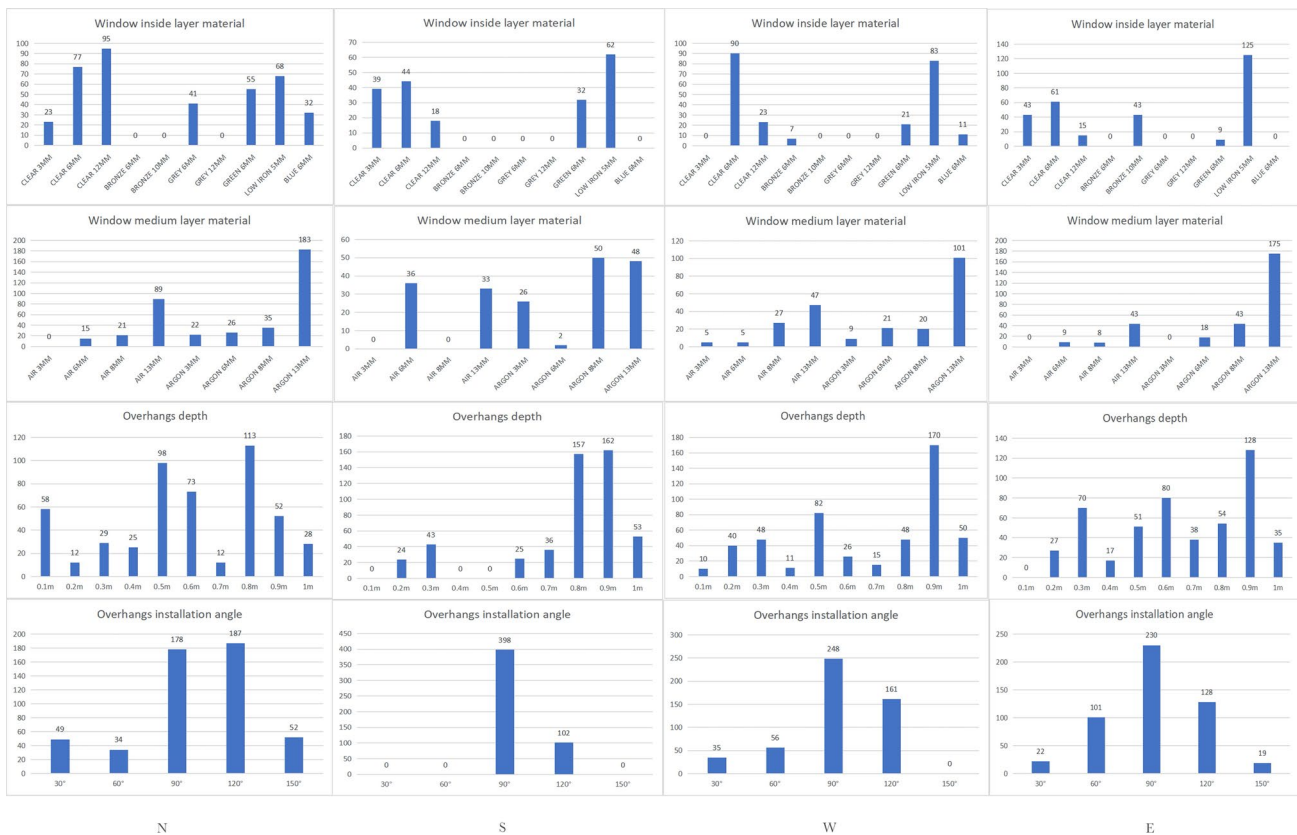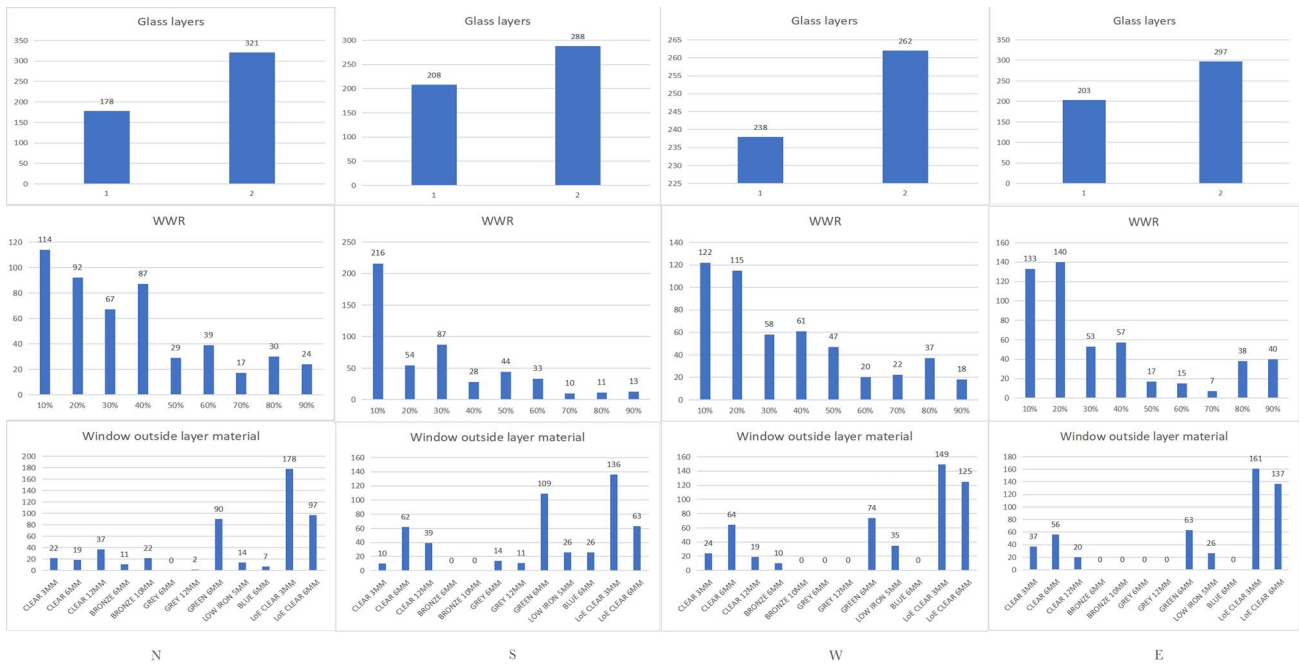
Fig. 22 Frequency of variables appearing in the optimization results in Guangzhou(a)
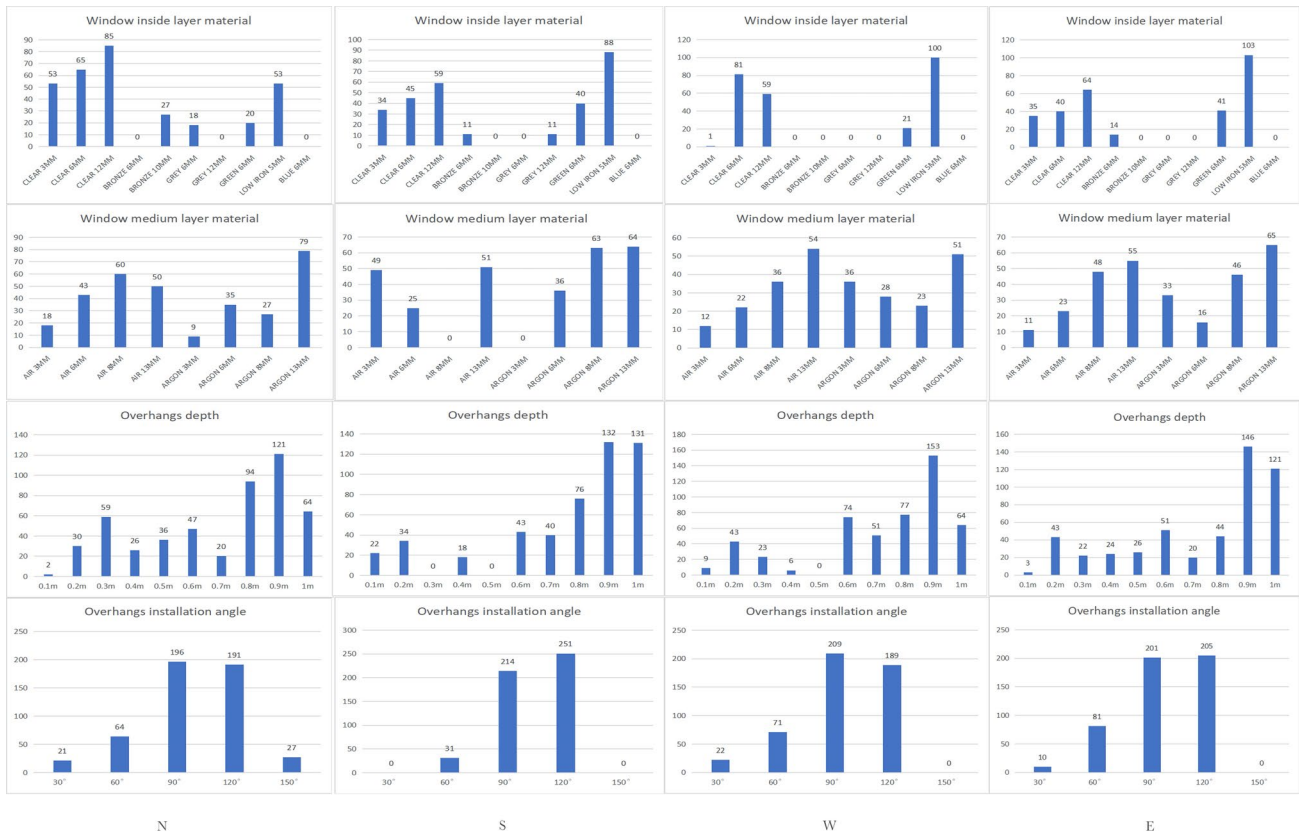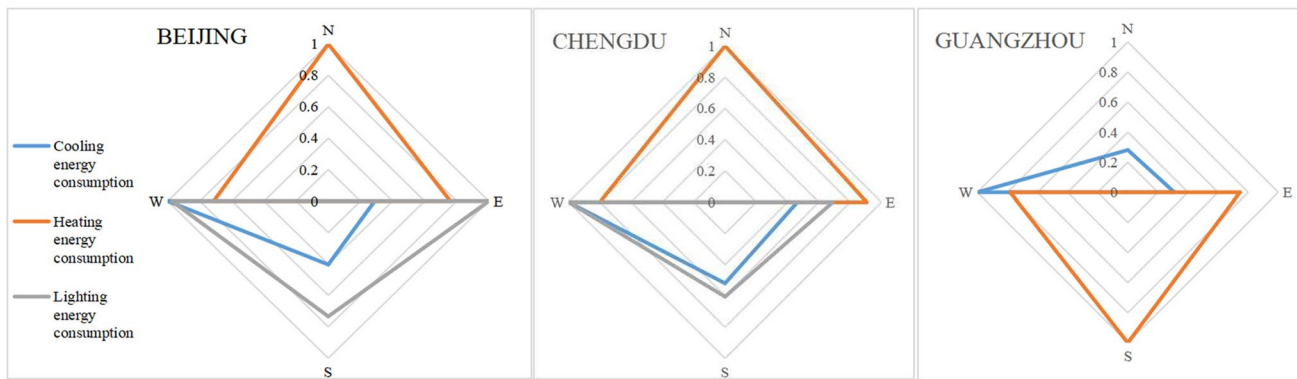

Fig. 23 Frequency of variables appearing in the optimization results in Guangzhou(b)

Fig. 24 Energy consumption in each direction

windows. It further illustrates the importance of considering single-layer and double-layer design in window and sunshade system design.

In the choice of window-to-wall ratio, the tendency of different climatic regions is different. The cold areas where Beijing is located are more likely to use windows with larger WWR, especially southward windows. In Figs. 6 and 7, it can be observed that the change trend of Pareto solution and design solution of southward windowing in Beijing is different from that of other directions and regions. It is because the heat gain of southward windowing to the room in winter is very obvious, and the increase in the refrigeration energy consumption is lower than that of heating energy consumption. So the visual performance is poor and the energy consumption is high when WWR is small, which leads to the trend in the figure. Hot summer and warm winter areas do not need heating, too large window-to-wall ratio will lead to a sharp increase in cooling energy consumption, so it is more likely to use a smaller WWR window system.

The outer glass of double-layer windows and the glass of single-layer windows are in direct contact with the outdoor environment, and their performance characteristics are the key to the performance of the window system. According to the optimization results, it can be concluded that LoE CLEAR 3 mm and LoE CLEAR 6 mm glass can be used in all four directions of the three climatic regions. Inner glass materials are mainly used for heat exchange with indoor environment, and CLEAR 6 mm, CLEAR 12 mm and LOW IRON 5 mm are suitable to be used as inner glass. BROZEN 10 mm, GREY 6 mm, GREY 12 mm and BLUE 6 mm glass should be carefully used as inner and outer glass.

The filling gas of double-layer glass can further improve the thermal insulation performance of the window system. From the distribution frequency of the optimal solution of Pareto, we can see that ARGON gas is more preferred to be used in Beijing and Chengdu, because ARGON, as an inert gas, has more stable performance than air and has lower thermal conductivity. It is beneficial to the thermal

insulation of windows. As there is no heating demand in Guangzhou, both AIR and ARGON can be used as filling gas.

The solar altitude angle, azimuth and solar radiation intensity are different in different climatic regions and directions, so the length and angle of the sunshade system will change accordingly. As shown in Figs. 18, 19, 20, 21, 22 and 23, shading configuration with longer shading length and angles of about 90°–120° are suitable for all three climatic zones, while shading of 30° and 150° is hardly selected. However, there are great differences in the selection trend among different orientations. The optimal solution set on the south side almost does not choose the shading configuration that is less than 90° and higher than 120°, and the shading length is longer, while the north side has a wider range of choices.

In order to show the impact of different window orientation on energy consumption in different climatic regions, Fig. 24 normalizes the cooling energy consumption, heating energy consumption and lighting energy consumption to draw a radar chart. (a), (b) and (c) are the distribution of energy consumption in Beijing, Chengdu and Guangzhou, respectively. Figure 4 (a) and (b) shows that the energy consumption of refrigeration on the west side and heating energy on the north side is the highest, and the refrigeration energy consumption on the south side of the (c) is higher. The lighting energy consumption in the west side of the three climatic regions is the highest. Therefore, extra attention should be paid to the design of the window system and sunshade system in the above three directions, and the performance can be further improved by optimizing the external maintenance structure such as the wall.

Discussion

In order to further elaborate the multi-objective optimization method and its results, and further demonstrate the effectiveness of the method, this paper compares the single-objective

minimum solution of the Pareto optimal solution with the final solution determined after multi-objective optimization. In the multi-objective optimization problem, the objective functions restrict each other. In most cases, it is unwise to pursue the minimum optimal scheme of a single objective, because it is difficult to meet all the requirements of all objectives at the same time. Linear weighted sum method is a commonly used multi-objective decision-making method in decision theory [48]. Some studies have shown that people tend to pay the same degree of attention to the goal of optimization in decision-making [49]. The goals considered in the discussion in this section are building energy consumption, visual performance, indoor thermal comfort and window sound insulation, which are expressed as follows:

$$F(x) = \alpha_i \sum_1^n \frac{f_i(x) - f_i(x)_{min}}{f_i(x)_{max} - f_i(x)_{min}}, \alpha_i \in [0, 1] \tag{10}$$

In this section, in order to further discuss the influence of sound insulation on the selection of window system, taking Chengdu area as an example, Tables 6 and 7 show the values of the optimal solution parameters selected according to this decision method without considering the sound insulation effect and considering the sound insulation effect, respectively. The values of α are $\alpha_1 = \alpha_2 = \alpha_3 = \frac{1}{3}$ and $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \frac{1}{4}$. Under this condition, the comparison results with the basic solution are shown in Table 8: Tables 5 and 6 show the values of window and sunshade system parameters without considering sound insulation and considering sound insulation, respectively. Table 7 shows that under the decision-making conditions set in this paper, after the multi-objective optimization program. Due to the simultaneous optimization of the three objectives, although the visual comfort of the basic scheme decreases slightly in the north, south and east directions, compared with the basic scheme, there is a great improvement in energy consumption and PMV. The energy consumption in four directions is reduced by about 8% to 9%, and the number of uncomfortable hours is reduced by 20% to 40%. Compared with not considering sound insulation, window systems with smaller window area and thicker glass thickness may be selected when considering sound insulation, which may further reduce energy consumption and PMV, but indoor visual performance will decline. Table 7 shows that the results of the two decision-making methods in Chengdu are the same or similar, the sound insulation effect of the window is of little significance as a decision-making condition, and sound insulation has important practical significance, so it can be added to the optimization process as a constraint in the future work.

In order to further verify the effectiveness of the multi-objective algorithm, Table 8 compares the final solution obtained by the single-objective optimal solution and the multi-objective weighted sum method in the Pareto solution set.

As given in Table 8, when only pursuing a single goal, its performance in the other two aspects is often poor. For example, in the north indoor visual effect optimal scheme, compared with the Pareto optimal solution, although the visual effect has been improved by 19.17%, the energy consumption has increased by 34.83%, and the number of uncomfortable hours has increased by 137.55%. Although the Pareto optimal solution is not optimal on a single goal, it can achieve a better level of three goals at the same time. In addition to the solutions proposed in the table above, Figs. 6, 7, 8, 9, 10 and 11 also provide many solutions. Designers can adjust decision assignments or decision methods according to actual needs in practical applications, so as to obtain different optimal solutions, and to achieve their desired performance.

Conclusion

Based on the combination of NSGA-II and EnergyPlus, this paper makes a multi-objective optimization of four facing window systems and shading configuration in three climatic regions of China. Compared to the previous research, energy consumption, visual performance and indoor uncomfortable hours are coupled to comprehensively evaluate their overall performance, and the effects of window layers, window sound insulation effect and window-to-wall ratio on the optimization are discussed. Compared with single-objective optimization, it can alleviate the conflict between objective functions and reduce the computational complexity, considering the interaction between different objectives, and taking different window materials as optimization parameters. Compared with the window system optimization method such as window U value, it has better practicability.

The optimization results show that the three optimization objectives restrict each other, the energy consumption is inversely proportional to the indoor visual performance, and the indoor thermal environment is inversely proportional to the visual performance. But there is no exact functional relationship among them, so it is necessary to use the multi-objective optimization method to obtain the Pareto optimal solution and comprehensively consider the design of its parameters. Through analysis, the influence of window–wall ratio on three objectives and the relationship between window singing effect and optimization objective are obtained, and the necessity of single and double layers as optimization parameters is proved. After further discussion, this paper thinks that the sound insulation effect of windows should be added to the process of multi-objective optimization as optimization constraints.

Table 5 Parameters of the optimal solution without considering the effect of sound insulation in Chengdu

	N	S	W	E
WWR	0.4	0.7	0.4	0.5
Glass layers	2	2	2	2
Window outside layer material	LoE CLEAR 6MM	LoE CLEAR 6MM	LoE CLEAR 3MM	LoE CLEAR 3MM
Window medium layer material	ARGON 13MM	ARGON 13MM	ARGON 13MM	ARGON 13MM
Window inside layer material	LOW IRON 5MM	CLEAR 12MM	CLEAR 6MM	CLEAR 3MM
Overhangs installation angle	120	90	90	90
Overhangs depth	0.8	0.8	0.5	0.9

Table 6 Parameters of the optimal solution considering the effect of sound insulation in Chengdu

	N	S	W	E
WWR	0.4	0.7	0.3	0.4
Glass layers	2	2	2	2
Window outside layer material	LoE CLEAR 6MM	CLEAR 12MM	LoE CLEAR 6MM	LoE CLEAR 3MM
Window medium layer material	ARGON 13MM	ARGON 13MM	ARGON 13MM	ARGON 13MM
Window inside layer material	LOW IRON 5MM	LOW IRON 5MM	CLEAR 6MM	LOW IRON 5MM
Overhangs installation angle	120	90	90	60
Overhangs depth	0.8	0.9	0.0	0.6

Table 7 Comparison of two optimal solutions and basic schemes in Chengdu

		Optimal1	Optimal2	Base case	Diff.1	Diff.2
N	Energy consumption (−)	207.66	207.66	229.80	− 9.63	− 9.63
	PMV (−)	237	237	416	− 43.03	−43.03
	UDI (+)	56.07	56.07	61.15	− 8.32	−8.32
	Sound insulation (+)	0.55	0.55	4.23	− 87.00	−87.00
S	Energy consumption (−)	195.05	195.05	207.78	− 6.13	−6.13
	PMV (−)	172	172	216	− 20.37	−20.37
	UDI (+)	57.45	57.45	55.58	3.27	3.27
	Sound insulation (+)	4.17	4.17	4.23	− 1.42	−1.42
W	Energy consumption (−)	222.55	216.68	245.96	− 9.52	−11.90
	PMV (−)	232	223	389	− 40.35	−42.67
	UDI (+)	51.95	47.93	56.33	− 7.76	−14.91
	Sound insulation (+)	2.53	5.47	3.96	− 36.11	27.61
E	Energy consumption (−)	217.45	217.34	236.81	− 8.18	−8.22
	PMV (−)	219	216	286	− 23.43	−24.48
	UDI (+)	54.78	51.49	55.91	− 2.02	−7.91
	Sound insulation (+)	− 0.81	1.84	3.96	− 122.98	−53.54

The method in this paper can provide designers with a variety of options for the design of windows and shading configuration, and also shows the values of window and shade design parameters that are not suitable or recommended in the four directions of the three climate zones, such as Bronze 10 mm, Grey 6 mm, Grey 12 mm and Blue 6 mm glass as inner and outer glass is an unwise choice. Through the comparison of the single-objective minimum value and the linear weighted sum method with equal weight, it is proved that this method can be used in the process of window design and reconstruction in different areas. Taking Chengdu as an example, the optimization results are

Table 8 Comparison of single-objective minimum scheme and final scheme in Chengdu

		$F_1(x)_{min}$	$F_2(x)_{min}$	$F_3(x)_{min}$	Final solution
N	Energy consumption	197.42	219.05	279.98	207.66
	Diff.(%)	− 4.93	5.48	34.83	–
	PMV	318	220	563	237
	Diff.(%)	34.18	− 7.17	137.55	–
	UDI	17.11	48.09	66.82	56.07
	Diff.(%)	− 69.48	− 14.23	19.17	–
S	Energy consumption	192.23	208.30	250.14	195.05
	Diff.(%)	− 1.45	6.79	28.24	–
	PMV	163	153	501	172
	Diff.(%)	− 5.23	− 11.05	191.28	–
	UDI	50.90	53.23	59.76	57.45
	Diff.(%)	− 11.4	− 7.31	4.02	–
W	Energy consumption	206.27	216.68	298.15	222.55
	Diff.(%)	− 7.32	− 2.64	33.97	–
	PMV	286	223	684	232
	Diff.(%)	23.28	− 3.88	194.83	–
	UDI	30.34	47.93	61.97	51.95
	Diff.(%)	− 41.6	− 7.74	19.29	–
E	Energy consumption	204.71	221.03	286.65	217.45
	Diff.(%)	− 5.86	1.65	31.82	–
	PMV	325	213	515	219
	Diff.(%)	48.4	− 2.74	135.16	–
	UDI	26.12	36.35	62.77	54.78
	Diff.(%)	− 52.32	− 33.64	14.59	–

analyzed in detail. Compared with the benchmark situation, the energy consumption in the four directions is reduced by about 8% to 9%, and the number of uncomfortable hours is reduced by 20% to 40%. It is proved that this method can not only provide designers with effective information of window design under the climatic conditions of the design area, but also provide corresponding eclectic design schemes for stakeholders.

The method of this paper is to further study the sound insulation effect of windows on the basis of building energy consumption, visual performance quality and indoor thermal environment as the objective function. In the next research, we can consider adding the sound insulation effect to the optimization process to obtain a more comprehensive Pareto optimal solution. At the same time, the calculation of sound insulation effect in this paper is formula method, which mostly uses empirical formula, and its accuracy needs to be improved. In future research, more accurate software simulation methods or more advanced schemes can be combined

with the multi-objective optimization method in this paper to make the results more accurate.

Declarations

References

1. IEA—International Energy Agency: IEA—International Energy Agency. https://www.iea.org. Accessed 29 May 2020
2. The 13th five-year plan for economic and social development of the People Republic of China. http://www.gov.cn/xinwen/2016-03/17/content_5054992.htm (2016). Accessed 29 May 2020
3. Echenagucia, T.M., Capozzoli, A., Cascone, Y., Sassone, M.: The early design stage of a building envelope: multi-objective search through heating, cooling and lighting energy performance analysis. Appl Energy **154**, 577–591 (2015). https://doi.org/10.1016/j.apenergy.2015.04.090
4. Mangkuto, R.A., Dewi, D.K., Herwandani, A.A., Koerniawan, M.D.: Faridah: design optimisation of internal shading device in multiple scenarios: case study in Bandung, Indonesia. J. Build. Eng. **24**, 100745 (2019). https://doi.org/10.1016/j.jobe.2019.100745
5. Aydn, D., Mihlayanlar, E.: A case study on the impact of building envelope on energy efficiency in high-rise residential building. Arch. Civ. Eng. Environ. **13**(1), 5–18 (2020). https://doi.org/10.21307/ACEE-2020-001
6. Zhai, Y., Wang, Y., Huang, Y., Meng, X.: A multi-objective optimization methodology for window design considering energy consumption, thermal environment and visual performance. Renew Energy **134**, 1190–1199 (2019). https://doi.org/10.1016/j.renene.2018.09.024
7. Sun, Y., Wilson, R., Wu, Y.: A review of transparent insulation material (TIM) for building energy saving and daylight comfort. Appl Energy **226**, 713–729 (2018). https://doi.org/10.1016/j.apenergy.2018.05.094
8. Xiaotu, L.: Architectural Physics. China Architecture & Building Press, Beijing (2010)
9. Manzan, M.: Genetic optimization of external fixed shading devices. Energy Build. **72**, 431–440 (2014). https://doi.org/10.1016/j.enbuild.2014.01.007
10. Lau, A.K.K., Salleh, E., Lim, C.H., Sulaiman, M.Y.: Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: the case of Malaysia. Int. J. Sustain. Built Environ. **5**(2), 387–399 (2016). https://doi.org/10.1016/j.ijsbe.2016.04.004
11. Al-Masrani, S.M., Al-Obaidi, K.M., Zalin, N.A., Aida Isma, M.I.: Design optimisation of solar shading systems for tropical office buildings: challenges and future trends. Sol. Energy **170**, 849–872 (2018). https://doi.org/10.1016/j.solener.2018.04.047
12. Goia, F., Haase, M., Perino, M.: Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective. Appl Energy **108**, 515–527 (2013). https://doi.org/10.1016/j.apenergy.2013.02.063
13. Alam, M.J., Islam, M.A.: Effect of external shading and window glazing on energy consumption of buildings in Bangladesh. Adv. Build. Energy Res. **11**(2), 180–192 (2017). https://doi.org/10.1080/17512549.2016.1190788

14. Khoroshiltseva, M., Slanzi, D., Poli, I.: A Pareto-based multi-objective optimization algorithm to design energy-efficient shading devices. Appl. Energy **184**, 1400–1410 (2016). https://doi.org/10.1016/j.apenergy.2016.05.015

15. Carlucci, S., Cattarin, G., Causone, F., Pagliano, L.: Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II). Energy Build. **104**, 378–394 (2015). https://doi.org/10.1016/j.enbuild.2015.06.064

16. Shi, X., Tian, Z., Chen, W., Si, B., Jin, X.: A review on building energy efficient design optimization rom the perspective of architects. Renew. Sustain. Energy Rev. **65**, 872–884 (2016). https://doi.org/10.1016/j.rser.2016.07.050

17. Susorova, I., Tabibzadeh, M., Rahman, A., Clack, H.L., Elnimeiri, M.: The effect of geometry factors on fenestration energy performance and energy savings in office buildings. Energy Build. **57**, 6–13 (2013). https://doi.org/10.1016/j.enbuild.2012.10.035

18. Li, Z., Chen, H., Lin, B., Zhu, Y.: Fast bidirectional building performance optimization at the early design stage. Build. Simul. **004**(011), 647–661 (2018)

19. Vallée, J., Ferrara, M., Astolfi, A., Fabrizio, E.: Trade-off between sound insulation performance and cost-optimality in a residential nZEB. Energy Procedia **140**, 57–66 (2017). https://doi.org/10.1016/j.egypro.2017.11.123

20. Wu, W., Guo, J., Li, J., Hou, H., Meng, Q., Wang, W.: A multi-objective optimization design method in zero energy building study: a case study concerning small mass buildings in cold district of China. Energy Build. **158**, 1613–1624 (2018). https://doi.org/10.1016/j.enbuild.2017.10.102

21. Wang, R., Lu, S., Feng, W.: A three-stage optimization methodology for envelope design of passive house considering energy demand, thermal comfort and cost. Energy **192**, 116723 (2020). https://doi.org/10.1016/j.energy.2019.116723

22. Bingham, R.D., Agelin-Chaab, M., Rosen, M.A.: Whole building optimization of a residential home with PV and battery storage in the Bahamas. Renew. Energy **132**, 1088–1103 (2019). https://doi.org/10.1016/j.renene.2018.08.034

23. Ochoa, C.E., Aries, M.B.C., van Loenen, E.J., Hensen, J.L.M.: Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Appl. Energy **95**, 238–245 (2012). https://doi.org/10.1016/j.apenergy.2012.02.042

24. Harmathy, N., Magyar, Z., Folić, R.: Multi-criterion optimization of building envelope in the function of indoor illumination quality towards overall energy performance improvement. Energy **114**, 302–317 (2016). https://doi.org/10.1016/j.energy.2016.07.162

25. Lee, J.W., Jung, H.J., Park, J.Y., Lee, J.B., Yoon, Y.: Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. Renew. Energy **50**, 522–531 (2013). https://doi.org/10.1016/j.renene.2012.07.029

26. Kwon, H.J., Yeon, S.H., Lee, K.H., Lee, K.H.: Evaluation of building energy saving through the development of venetian blinds' optimal control algorithm according to the orientation and window-to-wall ratio. Int. J. Thermophys. **39**(2), 30 (2018). https://doi.org/10.1007/s10765-017-2350-3

27. Zhao, J., Du, Y.: Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: a case study for office building in different climatic regions of China. Sol. Energy **206**, 997–1017 (2020). https://doi.org/10.1016/j.solener.2020.05.090

28. Crawley, D., Hand, J.: Contrasting the capabilities of building energy performance simulation programs. Build. Environ. **43**(4), 661–673 (2008). https://doi.org/10.1016/j.buildenv.2006.10.027

29. Goldstein, D.B., Eley, C.: A classification of building energy performance indices. Energy Effic. **7**(2), 353–375 (2014). https://doi.org/10.1007/s12053-013-9248-0

30. OpenStudio: OpenStudio. https://www.openstudio.net/ (2020). Accessed 10 May 2020

31. Ascione, F., Bianco, N., Mauro, G.M., Napolitano, D.F.: Retrofit of villas on Mediterranean coastlines: Pareto optimization with a view to energy-efficiency and cost-effectiveness. Appl. Energy **254**, 113705 (2019). https://doi.org/10.1016/j.apenergy.2019.113705

32. Nguyen, A., Reiter, S., Rigo, P.: A review on simulation-based optimization methods applied to building performance analysis. Appl. Energy **113**, 1043–1058 (2014). https://doi.org/10.1016/j.apenergy.2013.08.061

33. Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.A.: A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evolut. Comput. **6**(2), 182–197 (2002). https://doi.org/10.1109/4235.996017

34. Harkouss, F., Fardoun, F., Biwole, P.H.: Multi-objective optimization methodology for net zero energy buildings. J. Build. Eng. **16**, 57–71 (2018). https://doi.org/10.1016/j.jobe.2017.12.003

35. Delgarm, N., Sajadi, B., Delgarm, S., Kowsary, F.: A novel approach for the simulation-based optimization of the buildings energy consumption using NSGA-II: case study in Iran. Energy Build. **127**, 552–560 (2016). https://doi.org/10.1016/j.enbuild.2016.05.052

36. Gong, X., Akashi, Y., Sumiyoshi, D.: Optimization of passive design measures for residential buildings in different Chinese areas. Build. Environ. **58**, 46–57 (2012). https://doi.org/10.1016/j.buildenv.2012.06.014

37. Fang, Y., Cho, S.: Design optimization of building geometry and fenestration for daylighting and energy performance. Sol. Energy **191**, 7–18 (2019). https://doi.org/10.1016/j.solener.2019.08.039

38. Reinhart, C.F., Mardaljevic, J., Rogers, Z.: Dynamic daylight performance metrics for sustainable building design. Leukos **3**(1), 7–31 (2006). https://doi.org/10.1582/LEUKOS.2006.03.01.001

39. Carlucci, S., Causone, F., De Rosa, F., Pagliano, L.: A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renew. Sustain. Energy Rev. **47**, 1016–1033 (2015). https://doi.org/10.1016/j.rser.2015.03.062

40. Fanger, P.O., Melikov, A.K., Hanzawa, H., Ring, J.: Air turbulence and sensation of draught. Energy Build. **12**(1), 21–39 (1988)

41. Yucheng, K.: Building Sound Insulation Design: Air Sound Insulation Technology. China Architecture & Building Press, Beijing (2004)

42. Protection, M.O.U.A.: Code for design of sound insulation of civil buildings GB50118-2010 (2011)

43. Administration, S.E.P.: Environment quality standard for noise GB3096-2008. (2008)

44. Srinivas, M., Patnaik, L.M.: Genetic algorithms: a survey. Computer **6**(27), 17–26 (2002). https://doi.org/10.1109/2.294849

45. Lei, Y.S.Z.X.: MATLAB Genetic Algorithm Toolbox and Application. Xidian University Press, Xi'an (2005)

46. Ribeiro Filho, J.L., Treleaven, P.C.: Genetic-algorithm programming environments. Computer **27**(6), 28–43 (1994). https://doi.org/10.1109/2.294850

47. Ascione, F., Bianco, N., De Stasio, C., Mauro, G.M., Vanoli, G.P.: Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: a new approach to assess cost-optimality. Appl Energy **174**, 37–68 (2016). https://doi.org/10.1016/j.apenergy.2016.04.078

48. Delgarm, N., Sajadi, B., Kowsary, F., Delgarm, S.: Multi-objective optimization of the building energy performance: a simulation-based approach by means of particle swarm optimization (PSO). Appl Energy **170**, 293–303 (2016). https://doi.org/10.1016/j.apenergy.2016.02.141

49. Bre, F., Silva, A.S., Ghisi, E., Fachinotti, V.D.: Residential building design optimisation using sensitivity analysis and genetic

algorithm. Energy Build. **133**, 853–866 (2016). https://doi.org/10.1016/j.enbuild.2016.10.025