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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

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A R T I C L E I N F O

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A B S T R A C T

As a large energy-consuming part of the envelope, windows and shading system play a significant role in building savings. Once established in the primary design stage, it is difficult to make changes later, especially for high-rise buildings with large areas of glass. Moreover, strongly influenced by solar radiation, the configuration of windows and shading system conflicts with each other in terms of energy consumption and indoor comfort, the optimal configuration of windows and shading system under different climatic regions has not been well solved at yet. This paper proposes an easy-operation, useful, and efficient multi-objective optimization method, using a smart optimization algorithm NSGA-II in combination with DesignBuilder energy simulation software, especially beneficial for non-programming designers. In this research, a typical high-rise office building with a large area window has been selected as a case study. Building orientation, the configuration of windows and shading system, including materials for each layer of the double-layer window, installation angle and depth of overhangs have been taken into consideration, aiming to minimize the heating, cooling, lighting energy consumption and discomfort hours, and to find the mutual relationship between each other. A set of Pareto solutions can be obtained after optimization, and the most recommended variable parameters of windows and shading system in four cities representing severe cold climate, cold climate, hot summer and cold winter climate, and hot summer and warm winter climate can be identified, respectively. Besides, Pareto optimal solutions can give designers different scheme choices based on preferences, which are of great significance to provide guidance and suggestion for designers in the early design of buildings.

1. Introduction

1.1. Background

Nowadays, building accounts for 30%–40% of the total primary energy demand in the world (Sun et al., 2018), and with the improvement of people's living requirements and the increase of population, building energy consumption will continue to rise in the future. It is generally agreed that the early stage of design takes on a more important role, which strongly determines about 80% of a building's cost and high energy efficiency performance of buildings (Miles and Sisk., 2001; Wang and Rivard., 2006; Echenagucia et al., 2015). The envelope is direct contact with the external environment, and the average of 75% of the heat loss/gain occurs in the building envelope (Aydin and Mihlayanlar, 2020), so the selection of a high-performance envelope at this stage is essential. What's more, the building form once determined, it is hard to make relevant changes in the later stage.

Window is a special kind of component, whose overall heat transfer coefficient is normally five times greater than other components of the building envelope, and responsible for as much as 60% of the total energy consumption of a building (Sun et al., 2018; Lee et al., 2013). It has been reported that a large part of the net energy consumption of an office building is related to window heat loss and cooling demands induced by solar irradiance (Grynning et al., 2014). Window is a transparent envelope component, which allows a certain visible solar light to enter the room, reducing lighting energy consumption, and brings heating energy from solar radiation in winter, hence reduce heating energy consumption. However, heat brought by visible solar light into the room may result in indoor overheating, poor indoor thermal comfort environment, and increased cooling energy consumption in summer. Solar radiation through windows has different effects on building energy consumption and comfort in winter and summer, so

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the design of windows is a complicated multi-objective problem.

In the design of a window system, the main disadvantage of a single glass window is that it cannot provide enough heat resistance and usually lead to high cooling energy consumption in summer (Lai et al., 2017). To build good indoor thermal comfort environment and improve the energy efficiency of the building, adopting double-layer glass with a sandwich is a popular way to improve the thermal insulation of windows (Lai et al., 2017; Alam and Islam, 2017; Bastien and Athienitis, 2015). However, the use of high-performance exterior windows alone is far from enough to meet the requirements of building energy conservation and comfort, because the impact of exterior windows on the building is strongly interfered by solar radiation. As well-designed solar shading devices can provide considerable advantages (Goia and Haase, 2013), which can reduce the heat transfer to the building by blocking the solar radiation entering the room, and can also control the glare caused by excessive natural light, so as to improve the visual comfort (Alam and Islam, 2017), solar shading has become an important way for optimizing and controlling solar radiation entering the offices (Grynning et al., 2014). However, shading can also have negative effects, including increased lighting consumption and weakened winter solar gain, which in turn leads to increase energy consumption (Khoroshiltseva et al., 2016). Therefore, the design of shading devices should aim to optimize indoor comfort levels and reduce energy consumption, which is also a complicated high dimensional, multi-objective optimization problem (Khoroshiltseva et al., 2016; Kirimtat et al., 2019).

At present, designers tend to use a large area of glass in the pursuit of building aesthetic requirements and broad vision (Kiet Lau et al., 2016; Sadooghi and Kherani, 2018), especially for office buildings, causing high cooling load and poor indoor thermal comfort due to large solar gains in summer (Kiet Lau et al., 2016; Al-Masrani et al., 2018). Shading is considered as one of the most common strategies used by designers to improve the performance of the façade (Al-Masrani et al., 2018). Therefore, a high-performance window combined with shading is a necessary energy-saving measure and can strictly influence the internal comfort levels. Italian national regulations have clearly required the installation of exterior shading equipment or the use of low gain glass system coating (Manzan, 2014). However, windows and shading configuration are contradictory to the energy consumption of heating, cooling and lighting, and comfort under the action of solar radiation, it is particularly important to choose windows and shading configuration reasonably.

1.2. Existing research on optimization of windows or shading

Under the influence of solar radiation, the performance of windows and shading is mainly manifested in the building's heating, cooling, lighting energy consumption, and thermal comfort. There are some research works have been conducted on the single or multi-objective optimization design of windows or shading devices. Lee et al. (2013) optimized window systems considering different window types and property to examine its impact on building energy consumption for heating, cooling, and lighting in five typical climatic zones in China. Through regression analysis, simple charts for the relationship between window properties and building energy performance are presented as a function of heat transfer coefficient (U-value), solar heat gain coefficient (SHGC), visible transmittance, window to wall (WWR), solar aperture, effective aperture, and orientation, which can provide a basis for the selection of energy-saving windows. Su et al. (2010) analyzed the environmental impact of a typical office building over its entire life cycle, and finding out a suitable limited value for WWR of different orientation and window materials. Besides, there are large studies have assessed the contribution of different materials of windows for energy savings or natural light (Wang and Zhao, 2018; Hassouneh et al., 2010; Bojić and Yik, 2007; Taylor et al., 2009; Hee et al., 2015; Singh and Garg, 2009; Gasparella et al., 2011). Palmero-Marrero et al. (2010) optimized the effect of louver shading devices applied to different facades of buildings at different latitudes, and the effects of different shading configuration on building energy requirements during cooling and heating seasons were assessed under climatic conditions in Mexico (Mexico), Cairo (Egypt), Lisbon (Portugal), Madrid (Spain), and London (UK). Liu et al. (2019) optimized the use of shading devices on the opaque facade from the perspective of the length, quantity, and inclination of the overhangs, and explored the impact of different configurations of overhangs on the energy consumption for typical public rental buildings in Hong Kong, and the results show that when the sun visor is applied to the west facade, the energy saving potential reaches 8.0%. It also provides the energy saving coefficients within the optimal zones to guide the design of façade shading features in different urban contexts. Xie et al. (2017) also optimized the length and angle of overhangs, trying to balance the energy and daylighting performances. Samani et al. (2016) and Sghiouri et al. (2018) all studied the influence of shading on the indoor comfort, showing exterior shading is a highly effective measure in improving thermal comfort.

As the configuration of windows and shading involves multiple parameters, the value of each parameter is within a certain range of selection. Therefore, it would take a lot of computing time to conduct comparative research on the performance of windows and shading with the enumeration method. With the development of computer science, building engineering research combining building energy simulation program with optimization algorithm engine has been applied more and more widely. (Huang and Niu, 2016; Machairas et al., 2014; Zhai et al., 2019). According to the interactive influence of building orientation, window size and glass material on building performance, Zhai et al. (2019) optimized the configuration of windows from three aspects of energy savings, visual comfort and thermal comfort by using EnergyPlus coupling with NSGA-II algorithm, providing a set of optimal solutions for designers. Echenagucia et al. (2015) proposed a comprehensive approach to obtain detailed information about the envelope configuration in the early stages of building design, with the aim to minimize the energy requirements for heating, cooling and lighting by using genetic algorithm (GA), the results highlighted a small WWR is recommended of the building in all research sites. Delgarm et al. (2016) adopted EnergyPlus coupled particle swarm optimization algorithm to optimize the building's orientation, shading overhang specifications, window size, glass and wall materials in four major climatic regions of Iran, taking the building's cooling energy consumption, heating energy consumption, and lighting energy consumption as optimization objectives. Sghiouri et al. (2018) used TRNSYS and jEplus + EA tools to optimize overhangs, taking comfort and building energy conservation into consideration, and the results showed the optimized overhangs reduce the cooling demand by 4.1% for Casablanca's Mediterranean climate.

1.3. Motivation

The design of windows and shading is strongly influenced by solar radiation, which is mainly reflected in the energy consumption of heating, cooling, and lighting as well as indoor thermal comfort. Although there are many studies on the optimization of windows or shading design, most of these researches focus on the separation of windows and shading. On the other hand, most researchers tend to focus on one or several performances of buildings. Few studies comprehensively consider windows and shading in heating, cooling, lighting energy consumption and thermal comfort. This paper aims to solve the coupling optimal design problem of windows and shading configuration in high-rise buildings by considering the energy consumption of heating, cooling, and lighting energy consumption as well as thermal comfort. An original method was proposed, using the NSGA-II optimization algorithm on the jEplus + EA platform combined with DesignBuilder building energy simulation software, which is easy to operate, useful and efficient approach for building optimization design, especially for non-programming designers. Feasible solutions after

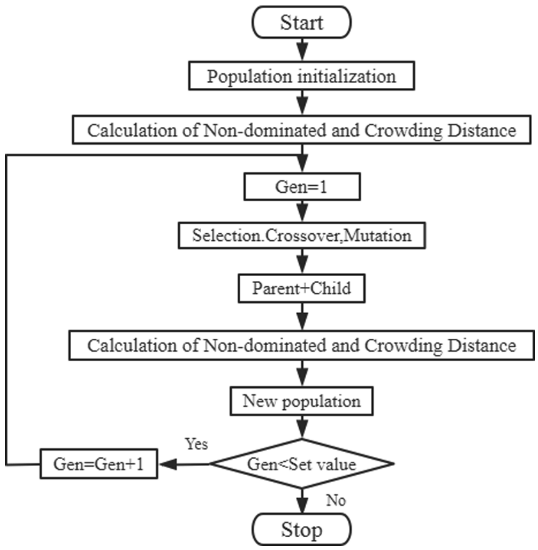


Fig. 1. Operation process of NSGA-II algorithm.

optimization can be provided for designers, and through two-dimensional (2D) and four-dimensional (4D) analysis, the features of each objective are obtained. According to designers' preferences, different weight coefficients can be assigned to each objective to identify the final scheme in decision.

The paper was organized as follows. In Section 2, the methodology of multi-objective optimization was proposed, then it was implemented into a case study in Section 3. The results were provided in Section 4, and the discussions were described in Section 5. Finally, conclusions were summarized in Section 6.

Fig. 3. Appearance diagram of the base case.

2. Methodology

2.1. Mathematical description of multi-objective optimization

In this paper, four objectives related to the configuration of windows and shading including heating, cooling, lighting energy consumption, and indoor thermal comfort need to be considered simultaneously, so it is a multi-objective optimization problem. A multi-

Table 1
The comparison of common optimization tools (Sghiouri et al., 2018; Nguyen et al., 2014).

Optimization tool	Open source	Parallel computing	Multi-objective optimization	User interface	Parametric study
jEplus + EA	Y	Y	Y	Y	Y
Matlab	N	Y	Y	Y/N	Y
GenOpt	Y	Y	N	N	Y
MOBO	Y	Y	Y	Y	N
TRNOPT	N	N	N	Y	Y
Rhinoceros Grasshopper	Y	Y	Y	Y	Y

"Y" means Yes; "N" means No.

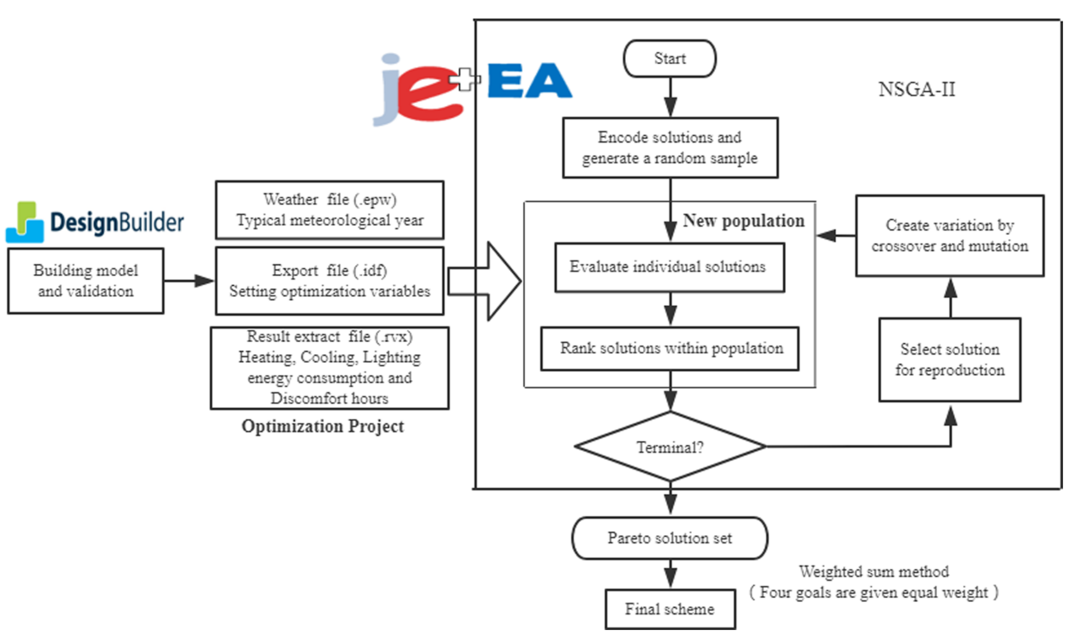


Fig. 2. Optimization process.

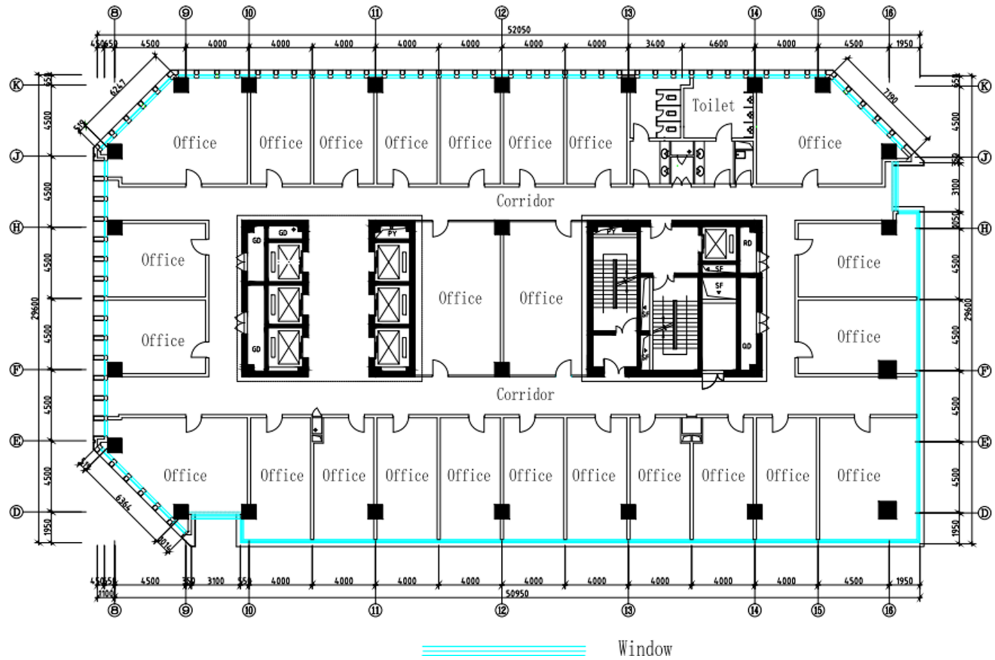


Fig. 4. Plan of the standard floor.

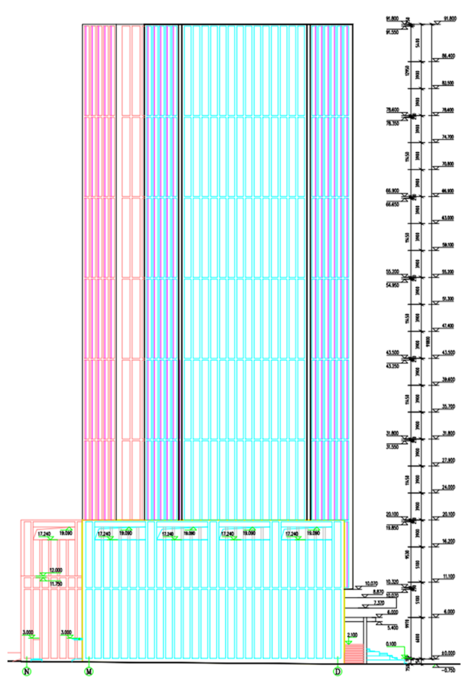


Fig. 5. The view of west facade window.

objective optimization problem is generally composed of multiple objective functions and some related equality and inequality constraints, and the detailed mathematical formula can be described as follows (Delgarm et al., 2016; Bingham et al., 2019; Taghdisian et al., 2015).

$$\begin{cases} \mathit{Minimize}\,\mathrm{F}(\vec{\mathrm{x}}) = [\mathrm{f_1}(\vec{\mathrm{x}}),\ \mathrm{f_2}(\vec{\mathrm{x}}),\ \cdots \mathrm{f_k}(\vec{\mathrm{x}})]^{\mathrm{T}} \\ \quad \mathit{Subjectto}: \begin{cases} \vec{\mathrm{g}}(\vec{\mathrm{x}}) \le 0 \\ \vec{\mathrm{h}}(\vec{\mathrm{x}}) = 0 \end{cases} \\ \vec{\mathrm{x}} \in \mathrm{R^n},\ \vec{\mathrm{f}}(\vec{\mathrm{x}}) \in \mathrm{R^k},\ \vec{\mathrm{g}}(\vec{\mathrm{x}}) \in \mathrm{R^m} \mathit{and}\, \vec{\mathrm{h}}(\vec{\mathrm{x}}) \in \mathrm{R^q} \\ \quad X = \{\vec{\mathrm{x}} | \mathrm{g_m}(\vec{\mathrm{x}}) \le 0,\ \mathrm{m} = 1,\ 2,\ 3 \cdots \mathrm{m}\} \\ \quad \{\mathrm{h_q}(\vec{\mathrm{x}}) = 0,\ \mathrm{q} = 1,\ 2,\ 3 \cdots \mathrm{q}\} \\ \quad S = \{\mathrm{F}(\vec{\mathrm{x}}) | \vec{\mathrm{x}} \in \mathrm{X}\} \end{cases} \tag{1}$$

where, $\vec{\mathrm{x}} \in \mathrm{R^n}$ is the vector of design variables and n is the number of decision variables. k is the number of objective functions, actually greater than or equal to 2, and $\vec{\mathrm{f}}(\vec{\mathrm{x}}) \in \mathrm{R^k}$ is an objective vector in which $\vec{\mathrm{f_i}}(\vec{\mathrm{x}})$: $\mathrm{R^n} \to \mathrm{R^1}$. m and $\vec{\mathrm{g}}(\vec{\mathrm{x}})$ are the number of inequality constraints and their vector, respectively. Similarly, q and $\vec{\mathrm{h}}(\vec{\mathrm{x}})$ are the number of equality constraints and their vector. Finally, X and S represent the feasible decision and criterion spaces, respectively.

It can be seen that objective functions, design variables, and constraints are the three elements of a multi-objective optimization problem, in which objective functions adopt a set of mathematical equations as indicators to evaluate the performance of the building system.

Table 2
The detailed building information.

Component	Description
Exterior wall	Rock wool board | density = 80 kg/m^3 | 90 mm thickness
Heat transfer coefficient (W/m^2·K)	0.45
Roof	Extruded polybenzene board | density = 25–32 kg/m^3 | 100 mm thickness
Heat transfer coefficient (W/m^2·K)	0.36
Exterior window	LoE hollow glass with 12 mm air layer
Heat transfer coefficient (W/m^2·K)	1.90
Interior partitions	Mineral wool, rock wool, glass wool board | density = 80 kg/m^3 | 100 mm thickness
Heat transfer coefficient (W/m^2·K)	0.50

In practical engineering design, decision-makers tend to optimize these performance indicators at the same time. And all objective functions $f_1(\vec{x}), f_2(\vec{x}), \cdots f_k(\vec{x})$ constitute the objective function vector $F(\vec{x})$ of multi-objective optimization.

Design variables $x_1, x_2, \cdots x_n$ are a set of vectors, which can be artificially specified and controlled and can have a direct impact on the performance of the engineering system. A set of design variables with different values form a vector $\{x_1, x_2, \cdots x_n\}^T$, and call it a solution to the optimization problem.

The constraint conditions include equality and inequality constraints. A set of design variables satisfying all constraint functions can be called a feasible solution, and all feasible solutions are constructed into the feasible domain of the optimization problem.

2.2. Non-dominated sorting genetic algorithm (NSGA-II)

GA was inspired by Darwin's theory of natural selection and Mendel's theory of genetics and was developed by Holland in the 1970s (Yu et al., 2015). It is a popular population-based optimization algorithm in the field of architecture, it can effectively deal with non-linear problems with discontinuity and local minimum (Machairas et al., 2014). The main idea of GA is to simulate the evolution process in nature. Each design variable $x_1, x_2, \cdots x_n$ represents a gene, and a combination of design variables $\{x_1, x_2, \cdots x_n\}^T$ constitute a chromosome. Starting from the initial population generated arbitrarily, through random selection, crossover and mutation operation, individuals that are more suitable for the environment are generated, and the population evolves to better and better regions. In this way, they continue to reproduce and evolve, and eventually converge to individuals more suitable for the environment to obtain the optimal solutions of the problem.

NSGA-II is an efficient variation of the basic GA (Kheiri, 2018), which was developed by Deb in 2000 (Deb et al., 2002). The algorithm proposes a fast, non-dominated sorting algorithm, which reduces the computational complexity. And it introduces a tournament selection strategy, which combines the parent generation with the child generation, then produces the next generation through competition, so as to ensure that excellent individuals will not be discarded in the process of evolution. An important process of the NSGA-II algorithm is the crowding distance, the crowding distance is used as the comparison criterion and can ensure the diversity of the population (Harkouss et al., 2018). The calculation formula of crowding distance is as follows:

$$L_d = L_d + \frac{f_m(i+1) - f_m(i-1)}{f_m^{max} - f_m^{min}} \tag{2}$$

where, L_d is crowding distance, $f_m(i+1)$ is (i + 1)-th objective function values, $f_m(i-1)$ is (i-1)-th objective function values, f_m^{max} is the maximum value of objective function, f_m^{min} is the minimum value of objective function.

Therefore, NSGA-II algorithm has been recognized to be one of the most efficient algorithms for multi-objective optimization (Echenagucia et al., 2015; Gou et al., 2018). The detailed operation process of NSGA-II algorithm is shown in Fig. 1.

Table 3
Occupant, lighting and equipment information.

	Occupant density (people/m^2)	Lighting density (W/m^2)	Indoor equipment power density (W/m^2)
Office	0.06	2.235	5.11
Meeting room	0.25	5.00	5.00
Corridor	0.02	0.73	0
Operation time	9:00–17:00 on weekdays		

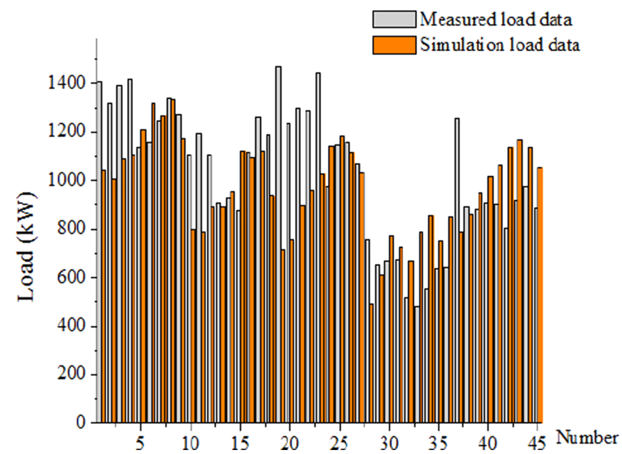


Fig. 6. The comparison of measured load and simulated load in summer.

2.3. Multi-criteria decision

The optimal solution of single-objective optimization is unique. The objective functions of multi-objective optimization are mutually restricted, so the solution is not unique. Pareto-dominance approach, which can enable the algorithm to optimize all the objectives simultaneously, and can provide a set of non-dominant optimal solutions (Gou et al., 2018).

In the decision theory, the weighted sum method (WSM) is the best-known multi-criteria decision-making approach (Delgarm et al., 2016), which is a common method to solve multi-objective decision problems. For each objective $f_i(\vec{x})$, different weight coefficients λ_i can be assigned to, representing different preferences of each objective for designers. The detailed expression is given in Eq. (3).

$$F(\vec{x}) = \lambda_i \sum_{i=1}^{i=K} \frac{f_i(\vec{x}) - f_i(\vec{x})^{min}}{f_i(\vec{x})^{max} - f_i(\vec{x})^{min}} \tag{3}$$

$$\sum_{i=1}^{i=k} \lambda_i = 1$$

$$\lambda_i \in [0, 1]$$

In this paper, K = 4, $f_1(\vec{x}), f_2(\vec{x}), f_3(\vec{x}), f_4(\vec{x})$ representing heating, cooling, lighting energy consumption, and indoor discomfort hours, respectively. λ_i refers to weight coefficient. Superscript min, max stands for minimum and maximum, respectively.

2.4. Structure of the multi-objective optimization

This paper adopted a method for combining an energy simulation

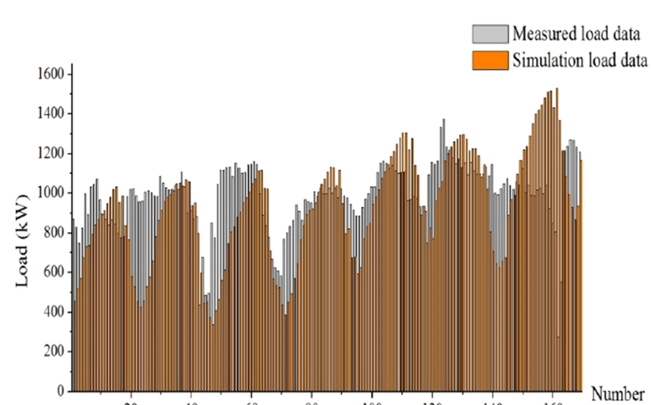


Fig. 7. The comparison of measured load and simulated load in winter.

Table 4
Climatic characteristics of the five climatic regions.

Climatic regions	SCC	CC	HS/CWC	HS/WWC	MC
Main index					
Average temperature of the coldest month	≤ −10 °C	0 °C~ −10 °C	0~10 °C	> 10 °C	0~13 °C
Average temperature of the hottest month	—	—	25~30 °C	25~29 °C	18~25 °C
Auxiliary index					
The days of daily average temperature ≤ 5 °C	≥145d	90~145d	0~90d	——	0~90d
The days of daily average temperature ≥ 25 °C	—	—	40~110d	100~200d	—
Representative city	Hohhot	Tianjin	Shanghai	Guangzhou	Not consider

Table 5
The schedule setting in four cities.

Cities	Hohhot	Tianjin	Shanghai	Guangzhou
Heating schedule	15 October~1 April	15 November~15 March	1 December~15 February	None
Cooling schedule	1 July~31 Aug	1 July~30 September	1 July~30 September	1 April~1 November

software and an optimization tool to investigate building optimization designs, which is a commonly used method for multi-objective optimization (Nguyen et al., 2014; Bingham et al., 2019). In this research, EnergyPlus, which is an open-source modular energy simulation code developed by the U.S. Department of Energy since 1996 (Crawley et al., 2011), is used to measure energy consumption and thermal comfort of the building. And due to the long development history supported by DOE, EnergyPlus has gained global acceptance by engineers and researchers (Kamal et al., 2019). The biggest drawback is that EnergyPlus is a parametric interface with poor visualization. Therefore, DesignBuilder (https://designbuilder.co.uk/software/product-overview) has been widely developed, which based on the EnergyPlus computing kernel and is one of the most comprehensive user interfaces for the EnergyPlus dynamic thermal simulation engine (Rahman et al., 2010). The algorithm of NSGA-II is implemented on the jEplus + EA platform. jEplus + EA is based on jEplus, which is an open-source tool originally developed to handle complex parametric simulation software for EnergyPlus (Zhang and Korolija, 2010), jEplus + EA coupled NSGA-II algorithm provides an effective approach for architectural design and engineering optimization. jEplus + EA can ensure the simultaneous optimization of four objectives proposed in this paper. Compared with Matlab and Rhinoceros Grasshopper, jEplus + EA doesn't need designers to write complicated programs in optimization engine, construct complex mathematical expressions of objectives by themselves or make complex connections, an excellent advantage for non-programming designers. Compared with MOBO, jEplus + EA is easy to operate, because MOBO has higher professional requirements for users (Palonen et al., 2013). Besides, jEplus + EA can implement parallel computing, greatly reducing computing time. The advantages of jEplus + EA can be found in comparison with other optimization engines, as shown in Table 1.

The detailed optimization process in this paper is as follows. A typical office model is established in DesignBuilder and validated using measured data at first; Afterwards, export EnergyPlus format input file (.idf), then as described in Fig. 2, set variable parameters in EnergyPlus format input file (.imf), write object function extraction files (.rvx) and download weather files (.epw) from EnergyPlus weather website (https://energyplus.net/weather), the three files are input into jEplus software, and then implement crossover and mutation operation in jEplus + EA platform to obtain multi-objective optimal Pareto solutions. According to Eq. (3), the final scheme can be determined, that is, the decision-maker can assign different weight coefficients (λ_i)in the Eq. (3). In this paper, the authors give equal weight to the objective functions to determine the final scheme. And this method to analyze the different optimal configuration of windows and shading system for high-rise office buildings was conducted in severe cold climate, cold climate, hot summer and cold winter climate, and hot summer and warm winter climate, respectively.

3. A case study implementation

3.1. Description of building model

A building located in Hohhot, China, is selected as a case study. It is a typical high-rise building, as can be seen in Fig. 3. The whole building consists of two parts, of which A is an office building and B is a hotel building. Due to the hotel building B is under construction, so this paper considered the office building A only. The orientation of the building is 12° north by west. The building has 21 floors above ground with a height of 91.8 m, whose 1–4 floors are podium buildings, 11–20 floors are standard floors, and the top floor is a dining room. The standard floor has 25 offices, an elevator hall, a staircase hall, and a toilet, with a total area of 1428.5 m^2, as shown in Fig. 4.

As mentioned above, DesignBuilder was used to establish the building geometry, divide thermal zones and set relevant parameters of thermophysical properties for building envelope, internal gains, shading overhangs system, lighting control system, and heating ventilation and air conditioning (HVAC) system. Four exterior walls have adjacent continuous exterior windows without shading devices. Therefore, there are no significant exterior obstructions seen from the

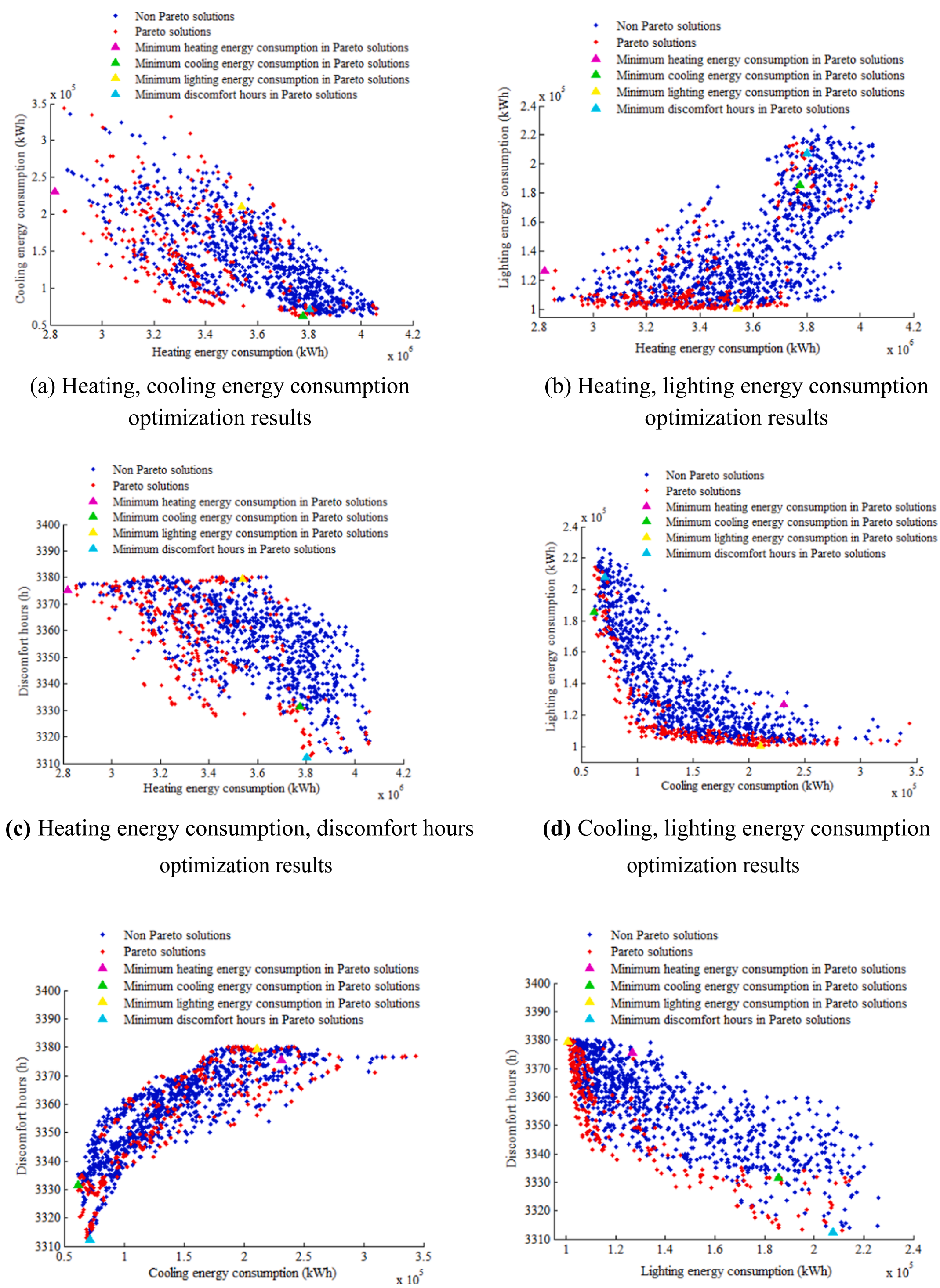
Table 6
Design variables parameters.

Parameters	Variables
Building orientation	{0,90,180,270}
Window inside layer material	Clear_3mm, Clear_6mm, Bronze_3mm, Bronze_6mm, Grey_3mm. Grey_6mm, Green_3mm, Green_6mm, Blue_6mm
Window outside layer material	Clear_3mm, Clear_6mm, Bronze_3mm, Bronze_6mm, Grey_3mm. Grey_6mm, Green_3mm, Green_6mm, Blue_6mm, LoE_Iron_3mm, LoE_Iron_4mm, LoE_Iron_5mm, LoE_Clear_3mm LoE_Clear_6mm, LoE_Tint_6mm, LoE_Spec_Sel_Clear_3mm, LoE_Spec_Sel_Clear_6mm, LoE_Spec_Sel_Tint_6mm, Ref_A_Clear_Hi_6mm, Ref_B_Clear_Hi_6mm, Ref_C_Clear_Hi_6mm, Ref_D_Clear_6mm, Ref_C_Tint_Hi_6mm, Ref_D_Tint_6mm, RYR_A_Clear_3mm, RYR_B_Clear_3mm, Ref_A_Tint_Hi_6mm, Ref_B_Tint_Hi_6mm, RYR_B_Clear_6mm
Window medium layer material	Air_6mm, Air_8mm, Air_13mm, Argon_6mm, Argon_8mm, Argon_13mm
Overhangs installation angle (°)	{0,10,20,30,40,50,60,70,80,90,100,110,120,130,140,150,160,170,180}
Overhangs depth (m)	{0.10,0.15,0.20,0.25,0.30,0.35,0.40,0.45,0.50,0.55,0.60,0.65,0.70,0.75,0.80,0.85,0.90,0.95,1.00}

Table 7
Parameters settings of NSGA-II.

Population size	Crossover rate	Mutation rate	Maximum generation
25	0.8	0.1	50

floor. The WWRs in the east, west, north, and south are 0.33, 0.50, 0.38, and 0.44, respectively. And the window adopts LoE hollow glass with air layer 12 mm in the base case, the diagram of the west facade window is shown in Fig. 5. More detailed building envelope information in the base case is given in Table 2. The occupant, equipment, and lighting density data were collected, as shown in Table 3 and the schedules of occupant, equipment, and daylighting are consistent with



(a) Heating, cooling energy consumption optimization results

(b) Heating, lighting energy consumption optimization results

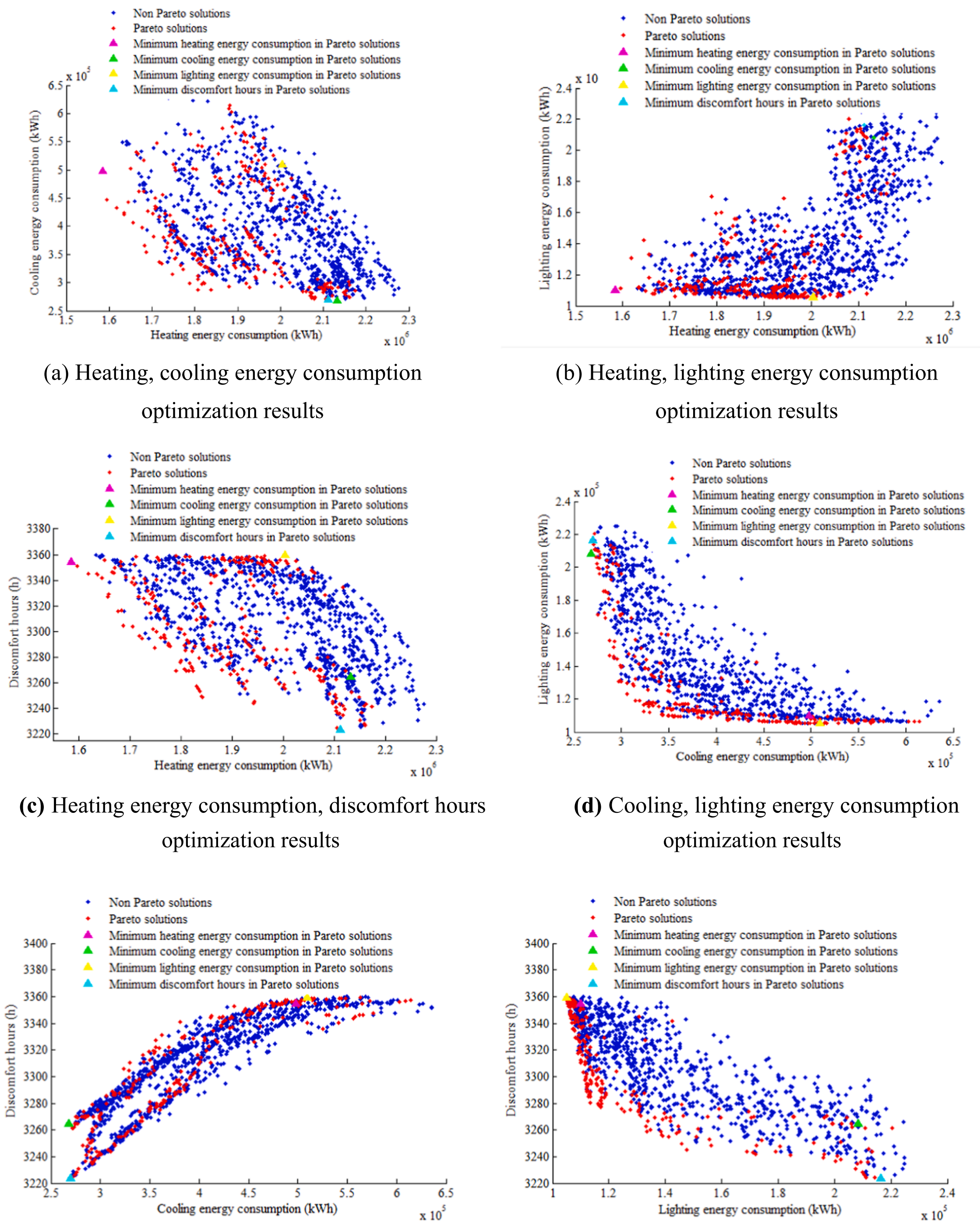
(c) Heating energy consumption, discomfort hours optimization results

(d) Cooling, lighting energy consumption optimization results

(e) Cooling energy consumption, discomfort hours optimization results

(f) Lighting energy consumption, discomfort hours optimization results

Fig. 8. Each of two objectives optimization results in Hohhot.



(a) Heating, cooling energy consumption optimization results

(b) Heating, lighting energy consumption optimization results

(c) Heating energy consumption, discomfort hours optimization results

(d) Cooling, lighting energy consumption optimization results

(e) Cooling energy consumption, discomfort hours optimization results

(f) Lighting energy consumption, discomfort hours optimization results

Fig. 9. Each of two objectives optimization results in Tianjin.

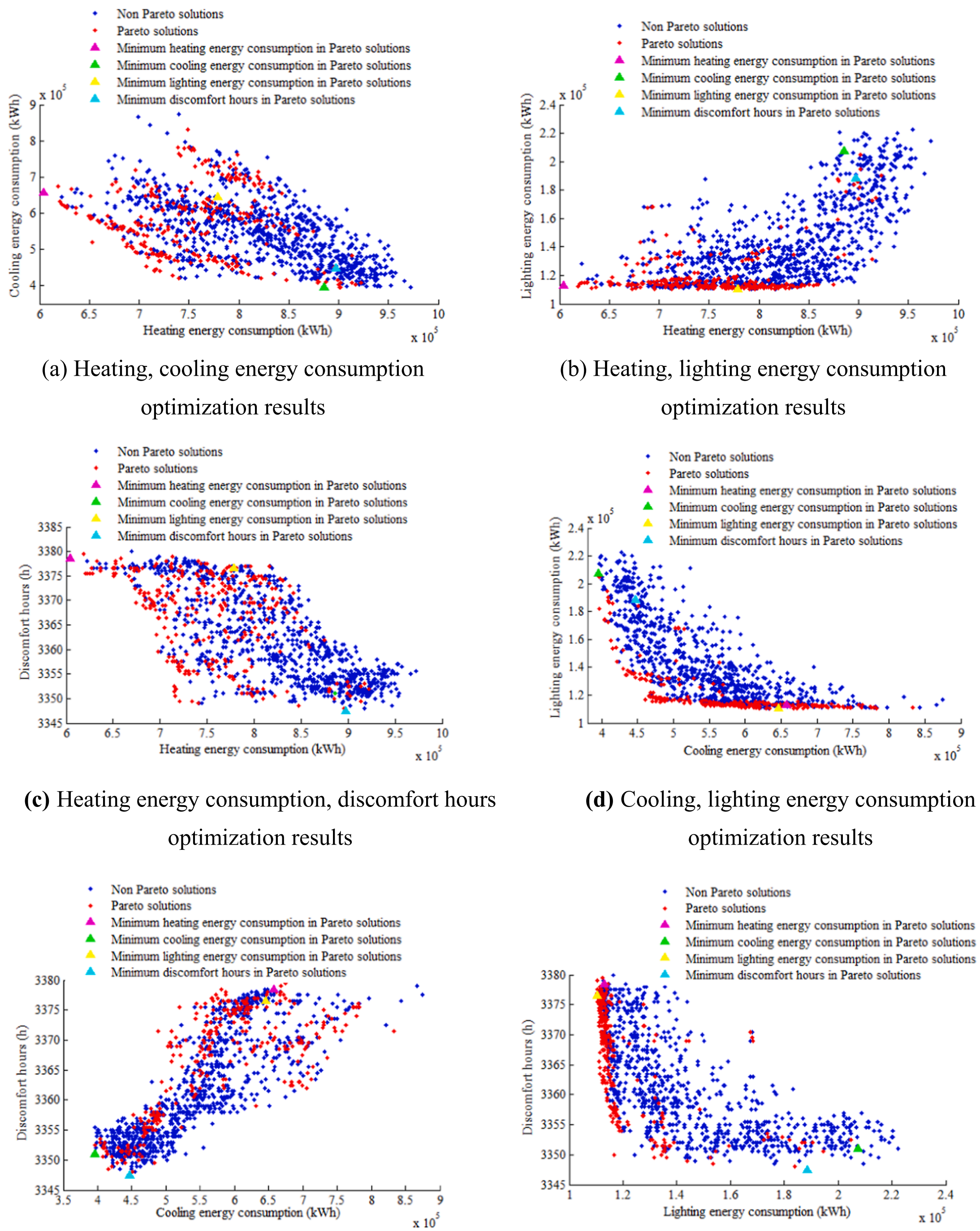
national design standards (Ministry of Construction of the People's Republic of China, Design standard for energy efficiency of public buildings GB50189-2005, 2005). The office building is mainly occupied from 9:00 a.m. to 5:00 p.m. on weekdays.

To evaluate the accuracy of modeling, ASHRAE Standard 14-2014 (ASHRAE, Measurement of Energy, Demand, and Water Savings; ASHRAE Guideline 14-2014) is widely accepted, in which normalized mean bias error (NMBE) and coefficient of variation of the root mean square error (CVRMSE) are two commonly used evaluation indicators. Detail expressions are presented as Eqs. (4) and (5). ASHRAE Guideline 14-2014 requires the NMBE within 10% and CVRMSE within 30% with hourly data, illustrating that the model established is in good agreement with the actual building.

$$\mathrm{NMBE} = 100 \times \frac{\sum_{i=1}^{n}(E_{si} - E_{mi})}{(n-p) \times \bar{E_m}} \tag{4}$$

$$\mathrm{CVRMSE} = 100 \times \frac{[\sum (E_{si} - E_{mi})^2/(n-p)]^{\frac{1}{2}}}{\bar{E_{\mathrm{m}}}} \tag{5}$$

where, E_{si} is the simulated data; E_{mi} is the measured data, $\bar{E_{\mathrm{m}}}$ is the



(a) Heating, cooling energy consumption optimization results

(b) Heating, lighting energy consumption optimization results

(c) Heating energy consumption, discomfort hours optimization results

(d) Cooling, lighting energy consumption optimization results

(e) Cooling energy consumption, discomfort hours optimization results

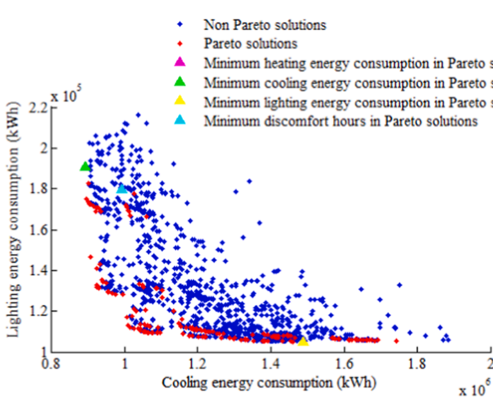
(f) Lighting energy consumption, discomfort hours optimization results

Fig. 10. Each of two objectives optimization results in Shanghai.

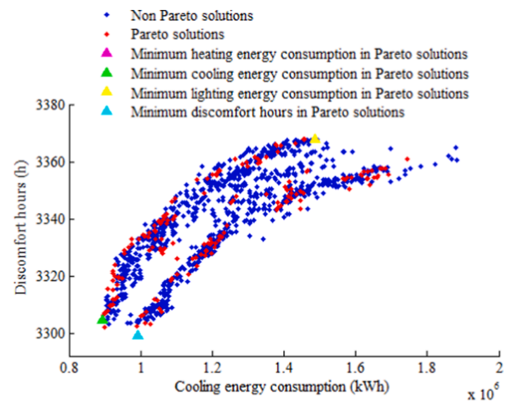
average value of measured data; n is the number of hours in this paper; p = 1.

The established DesignBuilder model of base case was verified by hourly load data measured on site. 45 groups of load data were collected in summer and 169 groups of load data collected in winter. The measured data were compared with the calculation results of DesignBuilder model, and the comparison results are shown in Figs. 6 and 7, respectively. Based on Eqs. (4) and (5), the calculation results of NMBE and CVRMSE in summer are 7.34% and 25.00%, respectively. In winter, the calculation result of NMBE is 6.20%, and the calculation result of CVRMSE is 27.10%. It can be seen that these errors are all within the requirements of ASHRAE Standard 14-2014, indicating that the established model is acceptable.

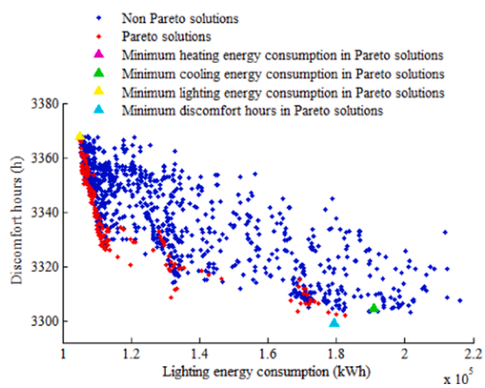
In order to solve the research objective established in this paper, the window system is designed with double-layer glass. The shading system adopts overhangs, whose position is above the window, and its left and right extensions are fixed at zero. It is generally considered that indoor illuminance above 500 lx can ensure indoor lighting requirements (Zhai et al., 2019; Delgarm et al., 2016; Ochoa et al., 2012). Therefore, when indoor illuminance is below 500 lx, artificial lighting will be turned on



(a) Cooling, lighting energy consumption optimization results



(b) Cooling energy consumption, discomfort hours optimization results



(c) Lighting energy consumption, discomfort hours optimization results

Fig. 11. Each of two objectives optimization results in Guangzhou.

to supplement, and then lighting energy consumption can be determined under different configurations of windows and shading system. As for the HVAC system, this paper adopted an ideal loads air system, the setpoint temperature is 26 °C in summer and 20 °C in winter.

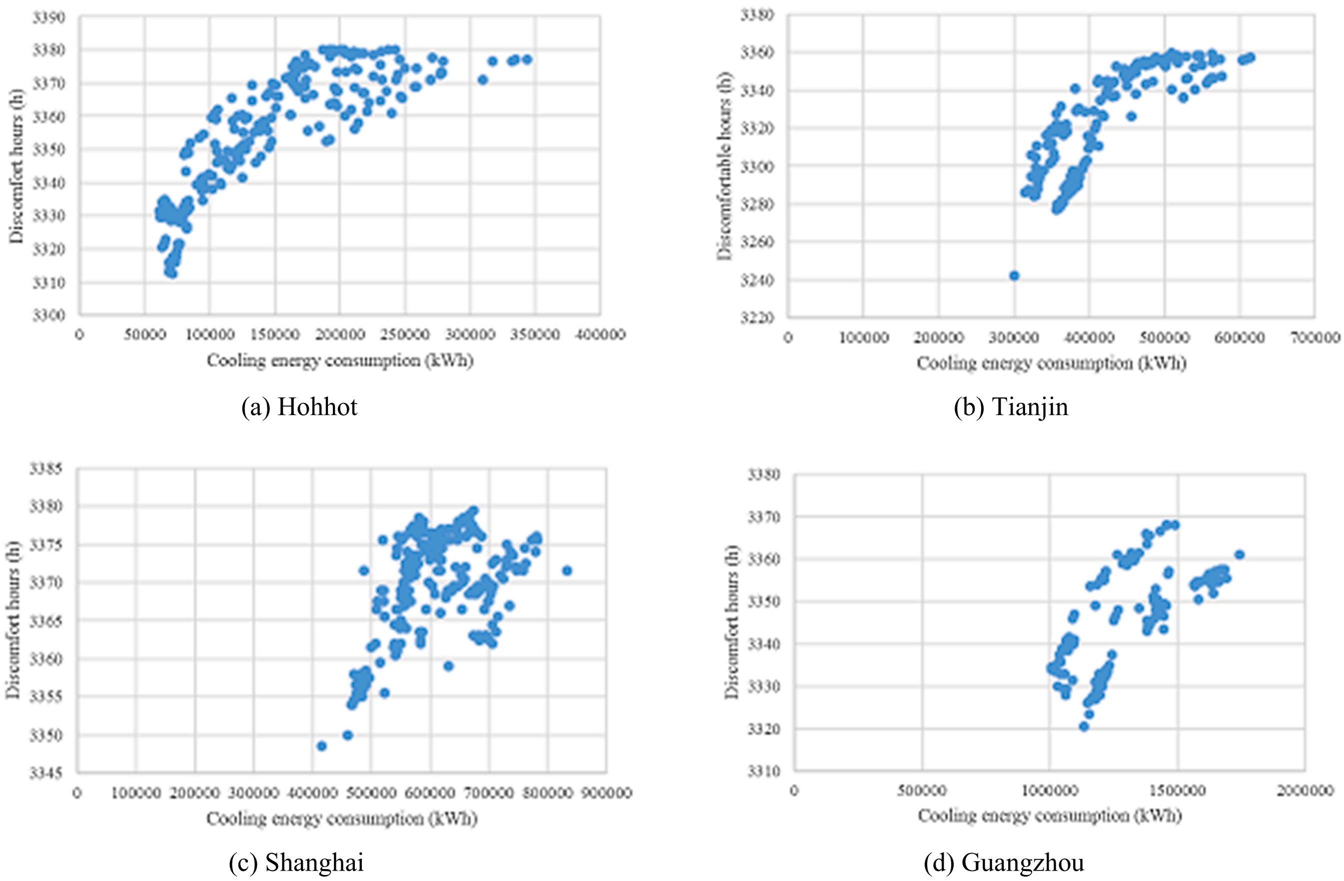
3.2. Major climatic regions in China

According to the average temperature of the coldest and hottest months of the year, the thermal climatic regions are determined, and supplementary classification is carried out according to the number of days when the daily average temperature is below 5 °C or above 25 °C (Gong et al., 2012). China is divided into five climatic regions. They are severe cold climate (SCC), cold climate (CC), hot summer and cold winter climate (HS/CWC), hot summer and warm winter climate (HS/WWC), and mild climate (MC), as shown in Table 4. Since there is less demand for air-conditioning in the mild climate, mild climatic region is not considered in this paper. Hohhot, Tianjin, Shanghai, and Guangzhou belong to the severe cold climatic region, cold climatic region, hot summer and cold winter climatic region, and hot summer and warm winter climatic region in China, respectively, and in these areas, these cities have good economic development and many high-rise buildings. What's more, these cities are directly under the central government or the provincial capital city, have certain typicality and representativeness. Therefore, Hohhot, Tianjin, Shanghai, and Guangzhou were chosen as representative cities of the four typical climatic regions. Four cities representing four typical climatic regions of China are set up in the same design parameters except for different cooling and heating season operation schedules, and the schedule settings in four climatic regions can be seen in Table 5.

3.3. Optimization settings

3.3.1. Design variables

Building orientation is essential for windows and shading design. The orientation design principle of the building is to maximize the natural light entering the room and reduce the demand for artificial lighting. At the same time, excessive direct sunlight should be avoided in summer to reduce indoor cooling load. Therefore, the orientation of the building will have an impact on the configuration of windows and shading system. In order to make the research more widely available, the configuration of windows and shading system under different orientations should be investigated. Glass material is a component of windows. Its feature and construction determine the key parameters of the window system and have an important impact on building energy consumption and indoor comfort. Compared with using the key parameters of windows, such as U-value, SHGC, and so on, to optimize window design, it is more feasible and practical to directly select glass material as the optimization variable in actual application. Therefore, this paper chose some commonly used glass material to discuss, and the relative glass material properties can be found in EnergyPlus database (WindowGlassMaterials.idf, WindowGasMaterials.idf). In order to



(a) Hohhot (b) Tianjin

(c) Shanghai (d) Guangzhou

Fig. 12. The relationship between cooling energy consumption and discomfort hours in four cities.

achieve the requirements of energy conservation and improvement of the thermal environment, it is not enough to rely solely on the window system, shading devices can greatly affect solar gains in a building and improve thermal and lighting comfort by selectively intercepting solar radiation and reducing undesirable glare (Khoroshiltseva et al., 2016). Compared with internal shading, external shading can directly block solar radiation from entering the room, and has a better and significant effect on energy conservation. According to some literature (Delgarm et al., 2016; Kirimtat et al., 2019), the installation angle and depth of the external shading overhangs are still worth considering. So the design variables in this paper are listed in Table 6.

3.3.2. Objective functions

As mentioned above, the configuration of windows and shading has a mutual influence on the heating, cooling, and lighting energy consumption of the building, as well as indoor thermal comfort. Therefore, it is very important to study the relationship between these four objectives, which are also the four objective functions of this optimization problem. Commonly used thermal comfort evaluation indexes include predicted mean vote (PMV), predicted percentage dissatisfied (PPD), discomfort hours, time-weighted discomfort and long-term percentage of dissatisfied (Longo et al., 2019). Based on the "Simple ASHRAE 55-2004" (ASHRAE STANDARD, Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineering, 2004), the number of discomfort hours in each zone of the building was collected and is used as the evaluation indicator of indoor comfort. Then the mathematical expression of the four objective functions can be described as following:

$$f_1(x) = Q_1 \tag{6}$$

$$f_2(x) = Q_2 \tag{7}$$

$$f_3(x) = Q_3 \tag{8}$$

$$f_4(x) = \sum_{i=0}^{8760} V_i \tag{9}$$

where, $f_1(x), f_2(x), f_3(x), f_4(x)$ are four objective functions, representing heating energy consumption, cooling energy consumption, lighting energy consumption, and discomfort hours, respectively. Q_1 is the heating energy consumption, kWh. Q_2 is the cooling energy consumption, kWh. Q_3 is the lighting energy consumption, kWh. V_i is "time not comfortable based on Simple ASHRAE 55-2004", which shows how many hours that the space is not comfortable for each zone under the criteria of assuming winter clothes, summer clothes, or both summer and winter clothes. That is, when the condition of "Simple ASHRAE 55-2004" is not satisfied at a certain hour time in each zoon of the building, its value is 1, Otherwise, it is 0.

3.3.3. Parameter settings of NSGA-II algorithm

There are some parameter settings in NSGA-II algorithm, including the population size, crossover rate, mutation rate and iteration number, which play a vital role in the algorithm, the selection of optimization parameters varies in different optimization problems.

In general, the crossover rate controls the dominant crossover operator in the process of optimization. Large crossover rate can make the generations to be fully crossed, but the possibility of damaging excellent individuals increase. Low crossover rate leads to slow evolution. If the crossover rate is too small, the algorithm will stagnate, and the general recommended value is between 0.4 and 0.99 (Lei et al., 2005).

Mutation rate controls the frequency of the mutation operation, which can help to repair and supply some genes that may be lost in the crossover process. A large mutation rate will increase the diversity of the population, but it may also destroy the excellent individuals. If the

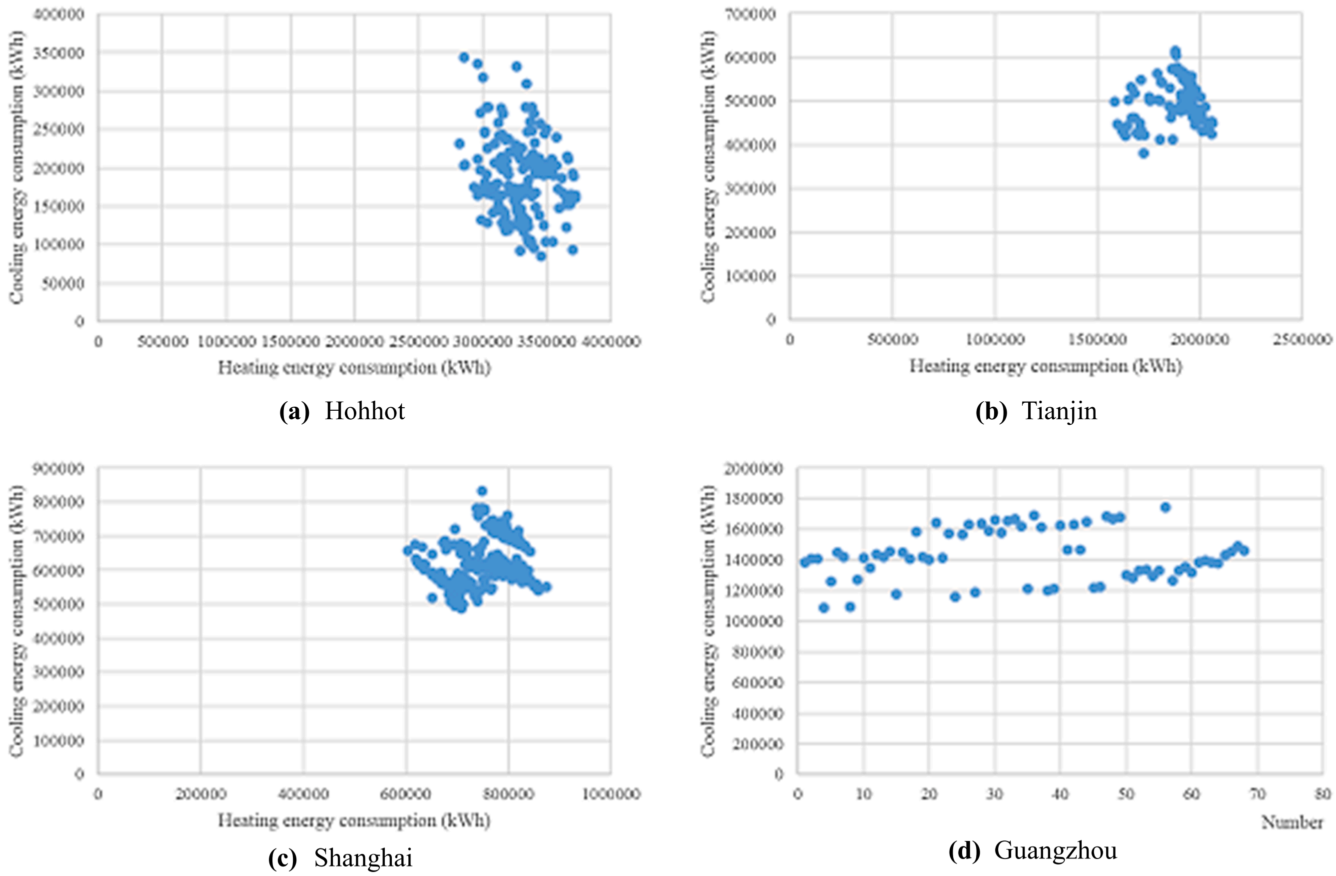


Fig. 13. The relationship between heating and cooling energy consumption in in four cities.

mutation rate is too small, immature convergence will easily occur, and the recommended value range is 0.0001~0.1 (Lei et al., 2005).

The size of the population and the number of iterations affect the convergence and computational efficiency of the algorithm. Small size will easily lead to local convergence, while a large size will reduce the computational speed. Generally, the recommended population size is 10~200 (Lei et al., 2005). Besides, some studies have shown that the population size setting can be 2~6 times of the design variables (Ascione et al., 2016). The setting of iteration times is generally considered from the reliability and calculation time of the algorithm. GA is a random algorithm, and the termination condition of the algorithm is usually to pre-set the number of iterations or to test the performance of the optimal individual in the population for specific problems. In general, two stopping criteria are often used: (i) when the algorithm exceeds 50 generations and (ii) when the average relative change of the fitness function is lower than the default tolerance 1e-6 (Papadopoulos et al., 2019).

Based on the analysis above, the parameter settings of NSGA-II adopted in this paper are shown in Table 7.

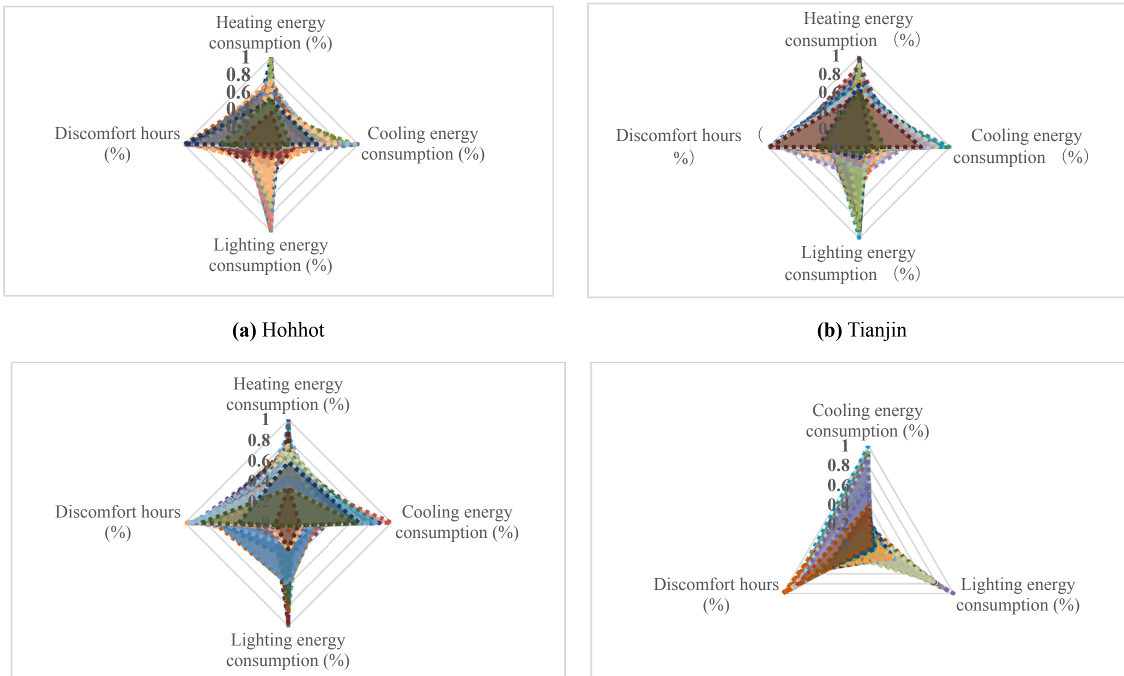
4. Results

4.1. Optimization results

4.1.1. 2D results analysis

This paper solved a four objective optimization problem. After 50 iterations, the optimization results have reached convergence. There are 287 Pareto optimal solutions in severe cold regions, 261 in cold regions, 306 in hot summer and cold winter regions, and 174 in hot summer and warm winter regions. To better understand the relationship between every two objectives, the optimal results for the configuration of windows and shading system in four climatic regions are rendered as 2D views, as shown in Figs. 8–11, respectively.

From the Figs. 8–11, it can be seen that objective functions conflict with each other. When one goal is optimal, it is not optimal for other goals. The similar trend changes of objective functions in the four climatic regions, indicating that the four objective functions affect each other through a certain coupling relationship. Due to the conflicting relationship among the four objectives, Pareto solutions mapped to the 2D views are not completely distributed on the boundary of the region. In comparison with every two objectives, the distribution of the Pareto optimal solutions between heating energy consumption and cooling energy consumption, between heating energy consumption and discomfort hours, as well as between cooling energy consumption and discomfort hours, is relatively scattered, indicating that the optimization of the two objectives in these three groups is greatly affected by the other two objectives, because four-objective optimization needs to consider four objective functions at the same time. There is an interesting phenomenon that the distribution of Pareto optimal solutions of heating energy consumption and lighting energy consumption in the four cities shows that with the increase of heating energy consumption, the lighting energy consumption of many Pareto optimal solutions changes little. To find the relationship between cooling energy consumption and discomfort hours of these Pareto solutions, these Pareto solutions were drawn in Fig. 12. It can be seen that in these Pareto solutions, there is a positive correlation between cooling energy consumption and discomfort hours. Besides, in Figs. 8–11, there is a hostile relationship between cooling energy consumption and lighting energy consumption, as well as between lighting energy consumption and discomfort hours, Pareto solutions are almost all on the leading edge, meaning that the coordination between the two conflicting objectives should be well done when making the plan decision. It can also be found that, as for the antagonistic relationship between lighting energy consumption and discomfort hours, a large number of Pareto solutions



(a) Hohhot **(b)** Tianjin

(b) Shanghai **(d)** Guangzhou

Fig. 14. The normalized objective functions value of the optimal schemes in four cities.

show that indoor comfort is greatly improved with a slight increase in lighting energy consumption. The relationship of heating energy consumption and cooling energy consumption of these Pareto solutions can be seen in Fig. 13. It can be seen that in this case, there is no obvious correlation between cooling energy consumption and heating energy consumption. What's more, the cooling or heating energy consumption of these Pareto solutions is relatively high.

4.1.2. 4D results analysis

To better demonstrate and understand the optimal value distribution of the four objective functions in optimal schemes, the values of the four objective functions in the optimal scheme are normalized and plotted in the radar map, as shown in Fig. 14. From the density of distribution in four directions in Fig. 14, it can be seen that the distribution of cooling energy consumption in Hohhot is relatively loose, that is, the change of cooling energy consumption in different optimal schemes is relatively large. Similarly, it can found that the change of discomfort hours in Tianjin is relatively small, and in Shanghai, the lighting energy consumption of many Pareto solutions is relatively loose. As for Guangzhou, the lighting energy consumption of each optimal scheme varies greatly.

Table 8 shows the range of each objective in the optimal solutions in four cities, in which, the range of the optimized value of lighting energy consumption is basically the same in the four cities. What's more, the number of discomfort hours is still high due to the multi-zone building with large area window configuration, it is hard to maintain all zones in a comfortable environment at the same time. However, there is no denying that optimizing the configuration of windows and shading system is still positive for reducing discomfort hours and improve indoor comfort, as the reduction of discomfort hours reflects the assurance of comfort in any zone of the building. The maximum optimal range of discomfort hours is 69 h in Guangzhou and the minimum optimal range of discomfort hours is 32 h in Shanghai. The optimization range of discomfort hours in Hohhot is 67.5 h, which is close to Guangzhou's, while the optimal range of discomfort hours in Tianjin is similar to that in Shanghai, showing that the fluctuation range of discomfort hours for high-rise buildings with large area windows is large in severe cold climatic regions and hot summer and warm winter climatic regions compared with cold climatic regions and hot summer and cold winter climatic regions.

4.2. Detailed optimal results analysis

The frequency distribution of optimization variables in Pareto solutions of windows and shading system in four representative cities is shown in Fig. 15. It can be seen that in these Pareto solutions. Some of the most recommended parameters for optimization variables in the four cities are the same, while others are very different. For example, the most recommended inner layer material of the window is Clear_3mm in the four cities. The most recommended parameters for the middle layer material of window, inner layer material of window, installation angle, and depth of overhangs in Hohhot and Tianjin are consistent. However, for Shanghai and Guangzhou, the most recommended parameters of building orientation, the outside layer material of window, the middle layer material of window, the installation angle, and the depth of overhangs are very different. The detailed

Table 8
The range value of each objective in the optimal solutions of four cities.

	Hohhot	Tianjin	Shanghai	Guangzhou
Heating energy consumption (GWh)	2.82~4.06	1.58~2.17	0.60~0.92	—
Cooling energy consumption (GWh)	0.06~0.34	0.27~0.61	0.40~0.83	0.89~1.74
Lighting energy consumption (GWh)	0.10~0.21	0.11~0.22	0.11~0.21	0.10~0.19
Discomfort hours (h)	3312.5~3380.0	3323.5~3359.5	3347.5~3379.5	3299.0~3368.0

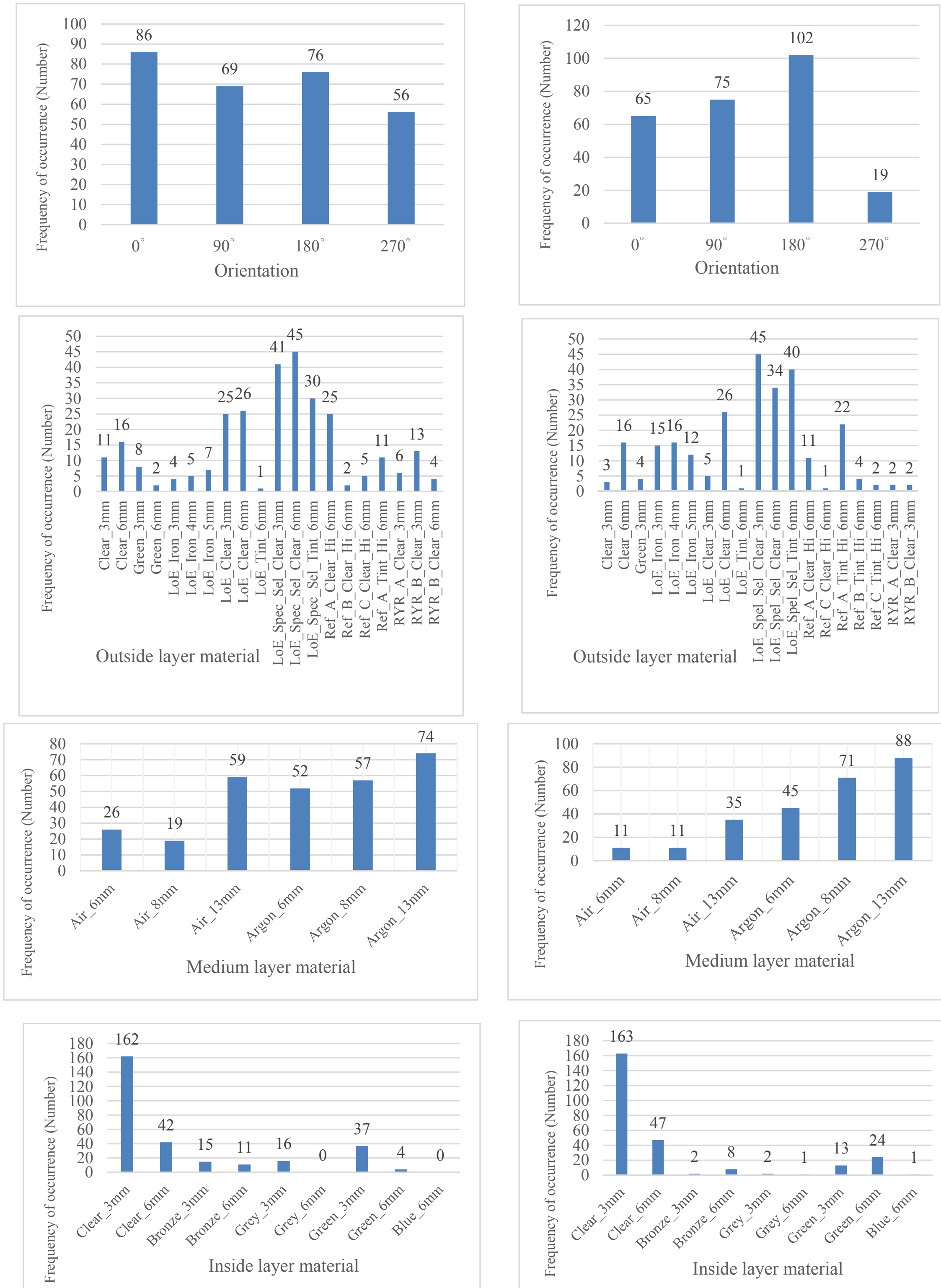


Fig. 15. Frequency of occurrence of variables in optimal schemes.

analysis results are given as follows.

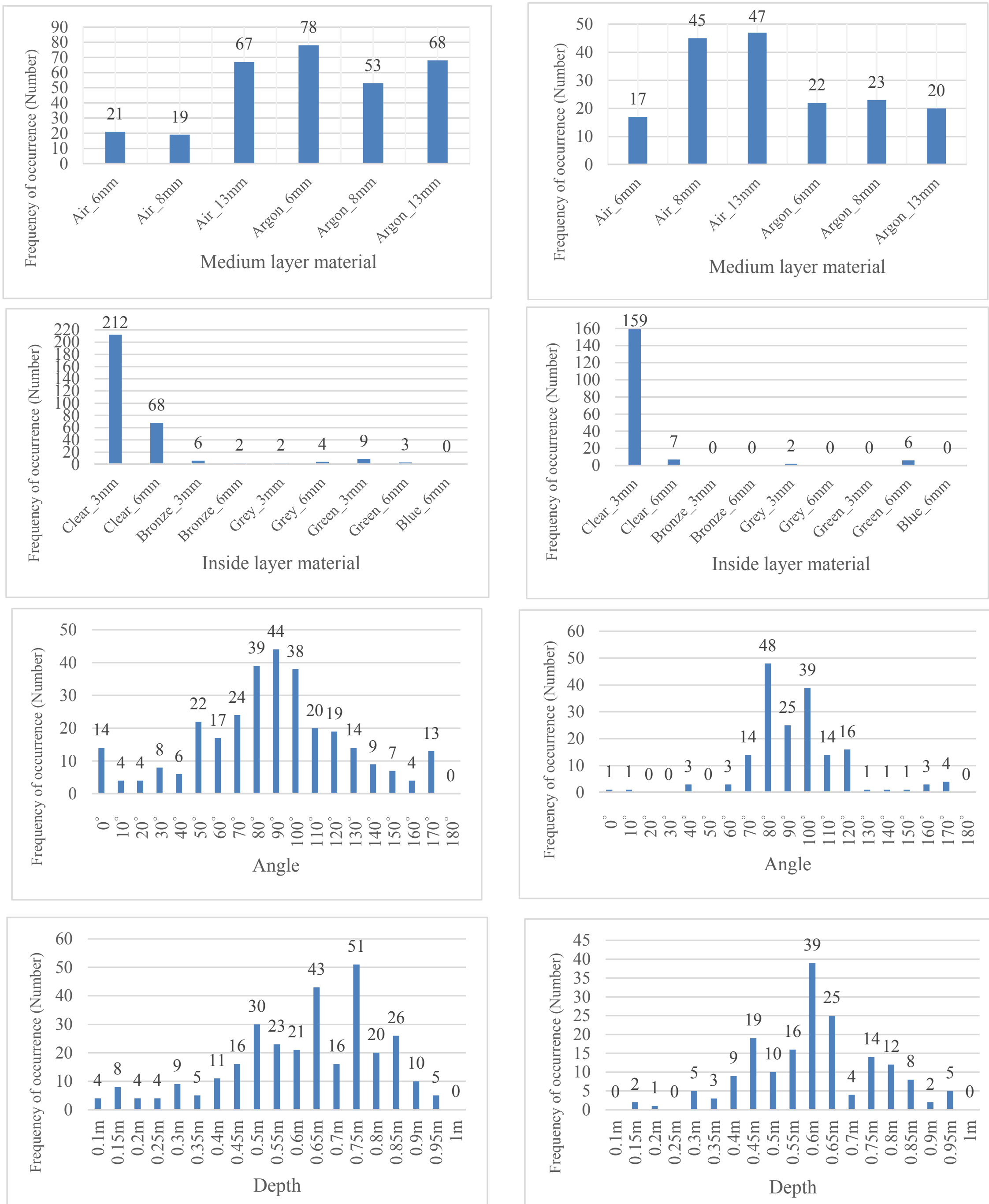
The subject of this study is a typical high-rise office building with large area windows in east, west, north, and south, which is in line with people's requirements of architectural aesthetics and broad vision. Since there are a large number of windows on all four exterior walls, suitable design schemes can be found in different orientations of the building. For Hohhot, there is little difference in the number of optimization schemes in the four orientations of east, west, north, and south. For Tianjin, Shanghai, and Guangzhou, the number of the optimal schemes produced in the 270° orientation is small. Due to the shape of the building, the 270° orientation results in larger areas of glass in the east–west orientation, and western sun phenomenon will cause the increase of room cooling load.

The outside layer glass is in direct contact with the exterior

Fig. 15. (*continued*)

environment, and its performance characteristics are critical to the window system. Therefore, design variables provide a variety of options for outside layer material of window. According to the optimization results, Bronze_3mm, Bronze_6mm, Grey_3mm, Grey_6mm, Blue_6mm, Ref_D_Clear_Hi_6mm, and Ref_D_Tint_Hi_6mm are not suitable for the use as outside layer material of window for four cities. LoE_Spec_Sel_Clear_3mm, LoE_Spec_Sel_Clear_6mm, and LoE_Spec_Sel_Tint_6mm were found to be more widely used in the optimal schemes of Hohhot and Tianjin. LoE _Clear_6mm is better for Shanghai, and LoE_Spec_Sel_Clear_3mm is more recommended for Guangzhou.

In order to improve the heat insulation performance of the window system, two commonly used filling gases, air and argon, are considered. From the distribution of the optimal solutions, it can be seen that argon



(c) Shanghai (d) Guangzhou

Fig. 15. (*continued*)

gas is more suitable as the filling gas in Hohhot and Tianjin. This is because argon gas is an inert gas with a more stable and lower thermal conductivity than air, which contributes to a low U-value for windows. For Shanghai, neither heating or cooling energy consumption shows a clear dominant relationship. From the point of heat insulation performance, air_13mm, argon_6mm, and argon_13mm are recommended. For Guangzhou, there is no requirement for heating, the more recommended middle layer material of window is air_8mm and air_13mm.

The material of inner glass is mainly used for heat exchange with the indoor environment. From the perspective of economic application, several inner glass materials are provided for selection. It can be seen in Fig. 15, Clear_3mm is the most suitable choice in optimal results for four cities. What's more, in terms of cost, Clear_3mm also has incomparable advantages.

Under the combined influence of the solar altitude angle, azimuth angle, and solar radiation, the installation angle of exterior shading overhangs will vary in different climatic regions. In the optimal schemes, it can be seen that the most recommended installation angle of overhangs in Hohhot and Tianjin is 110°. In Shanghai, the most suitable angle is 90°. In Guangzhou, 80° angle can be deemed as the first choice. It can be seen that the most recommended shading installation angle shows a decreasing trend from severe cold climatic regions to hot summer and warm winter climatic regions.

Table 9
The design parameters in single objective optimal scheme in Pareto solutions.

	Design variable	$f_1(x)_{min}$ in Pareto solutions	$f_2(x)_{min}$ in Pareto solutions	$f_3(x)_{min}$ in Pareto solutions	$f_4(x)_{min}$ in Pareto solutions
Hohhot	Building orientation	0°	0°	180°	**90°**
	Window inside layer material	Bronze_6mm	Green_3mm	Clear_3mm	Green_3mm
	Window medium layer material	Argon_13mm	Argon_13mm	Air_6mm	Argon_13mm
	Window outside layer material	LoE_Clear_3mm	Ref_A_Clear_Hi_6mm	LoE_Iron_3mm	Ref_A_Tint_Hi_6mm
	Overhangs installation angle	0°	130°	40°	110°
	Overhangs depth	0.85 m	0.95 m	0.45 m	0.95 m
Tianjin	Building orientation	0°	0°	180°	180°
	Window inside layer material	Clear_3mm	Clear_6mm	Clear_3mm	Green_6mm
	Window medium layer material	Argon_13mm	Argon_8mm	Air_6mm	Argon_13mm
	Window outside layer material	LoE_Clear_6mm	Ref_A_Tint_Hi_6mm	LoE_Iron_3mm	Ref_A_Tint_Hi_6mm
	Overhangs installation angle	20°	130°	10°	170°
	Overhangs depth	0.90 m	1.00 m	0.15 m	0.95 m
Shanghai	Building orientation	180°	0°	180°	270°
	Window inside layer material	Clear_6mm	Clear_3mm	Clear_3mm	Green_3mm
	Window medium layer material	Argon_13mm	Argon_13mm	Argon_6mm	Argon_13mm
	Window outside layer material	RYR_B_Clear_6mmm	Ref_A_Tint_Hi_6mm	LoE_Iron_5mm	Ref_B_Tint_Hi_6mm
	Overhangs installation angle	0°	160°	50°	130°
	Overhangs depth	0.85 m	0.80 m	0.50 m	0.75 m
Guangzhou	Building orientation	—	0°	180°	270°
	Window inside layer material	—	Green_6mm	Clear_3mm	Green_6mm
	Window medium layer material	—	Argon_13mm	Air_13mm	Argon_13mm
	Window outside layer material	—	Ref_A_Clear_Hi_6mm	LoE_Iron_4mm	Ref_A_Clear_Hi_6mm
	Overhangs installation angle	—	170°	10°	100°
	Overhangs depth	—	0.80 m	0.65 m	0.65 m

Table 10
Comparison between minimum of each objective in Pareto solutions and base case.

	Optimal objective	$f_1(x)_{min}$	$f_2(x)_{min}$	$f_3(x)_{min}$	$f_4(x)_{min}$	Base Case
Hohhot	**Heating consumption (GWh)**	2.82	3.78	3.54	3.80	3.00
	Diff. (%)	−6.00	26.00	18.00	26.67	—
	Cooling consumption (GWh)	0.23	0.06	0.21	0.071	0.32
	Diff. (%)	−28.13	−81.25	−34.38	−77.81	—
	Lighting consumption (GWh)	0.13	0.19	0.101	0.21	0.104
	Diff. (%)	25.00	82.69	−2.88	101.92	—
	Total consumption (GWh)	3.39	4.24	4.07	4.29	3.64
	Diff. (%)	−6.87	16.48	11.81	17.86	—
	Discomfort hours (h)	3375.5	3331.5	3379.5	3312.5	3380
	Diff. (%)	−0.13	−1.43	−0.01	−2.00	—
Tianjin	**Heating consumption (GWh)**	1.58	2.13	2.00	2.11	1.66‘
	Diff. (%)	−4.82	28.31	20.48	27.11	—
	Cooling consumption (GWh)	0.50	0.268	0.51	0.270	0.60
	Diff. (%)	−16.67	−55.33	−15.00	−55.00	—
	Lighting consumption (GWh)	0.11	0.21	0.105	0.22	0.12
	Diff. (%)	−8.33	75.00	−12.50	83.33	—
	Total consumption (GWh)	2.41	2.82	2.83	2.81	2.60
	Diff. (%)	−7.31	8.46	8.85	8.08	—
	Discomfort hours (h)	3354.5	3264.5	3359.5	3223.5	3380.0
	Diff. (%)	−0.75	−3.42	−0.61	−4.63	—
Shanghai	**Heating consumption (GWh)**	0.60	0.89	0.78	0.90	0.65
	Diff. (%)	−7.69	36.92	20.00	38.46	—
	Cooling consumption (GWh)	0.66	0.40	0.65	0.45	0.72
	Diff. (%)	−8.33	−44.44	−9.72	−37.50	—
	Lighting consumption (GWh)	0.113	0.207	0.110	0.19	0.13
	Diff. (%)	−13.08	59.23	−15.38	46.15	—
	Total consumption (GWh)	1.59	1.70	1.75	1.75	1.71
	Diff. (%)	−7.01	−0.58	2.34	2.34	—
	Discomfort hours (h)	3378.5	3351.0	3376.5	3347.5	3377.0
	Diff. (%)	0.04	−0.77	−0.01	−0.87	—
Guangzhou	**Cooling consumption (GWh)**	—	0.89	1.49	0.99	1.59
	Diff. (%)	—	−44.03	−6.29	−37.74	—
	Lighting consumption (GWh)	—	0.19	0.10	0.18	0.11
	Diff. (%)	—	72.72	−9.09	63.64	—
	Total consumption (GWh)	—	1.30	1.81	1.39	1.91
	Diff. (%)	—	−31.94	−5.24	−27.23	—
	Discomfort hours (h)	—	3304.5	3368	3299	3367.0
	Diff. (%)	—	−1.86	0.03	−2.02	—

Table 11
The optimal design parameters for multi-objective final solution.

Parameter	Unit	Hohhot	Tianjin	Shanghai	Guangzhou
Building orientation	°	0	0	0	270
Window inside layer material	–	Clear_3mm	Clear_3mm	Clear_3mm	Clear_3mm
Window medium layer material	–	Air_13mm	Argon_13mm	Argon_13mm	Argon_13mm
Window outside layer material	–	LoE_Spec_Sel Clear_6mm	LoE_Spec Sel_Clear_3mm	LoE_Spec Sel_Tint_6mm	LoE_Spec Sel_Tint_6mm
Total solar transmission (SHGC)		0.426	0.436	0.285	0.285
Direct solar transmission		0.373	0.389	0.225	0.225
Light transmission		0.695	0.704	0.416	0.416
U-value		1.639	1.353	1.345	1.345
Overhangs installation angle	°	120	110	110	110
Overhangs depth	m	0.85	1.00	0.40	0.70

The depth of overhangs is too short to play the role of shading. Too long will increase the cost and also lead to poor lighting performance in the room. Undoubtedly, the shading effect is not only the installation angle but also the installation depth. Most recommend depth of the overhangs in four cities is 0.85 m, 0.85 m, 0.75 m, and 0.6 m, respectively.

5. Discussion

5.1. Single objective optimal scheme in Pareto solutions

In Pareto solutions, the scheme of each objective function minimum is selected to obtain the optimal solution in each case, and the optimal results of single objective minimum design scheme in Pareto solutions are marked triangle and labeled in Figs. 8–11. Table 9 shows the detailed design parameters in single objective optimal scheme in Pareto solutions. The results of the optimal scheme for each objective in Pareto solutions are compared with the results of the basic case, as shown in Table 10.

It can be seen from Table 10 that, compared with the basic model, the optimal Pareto solution with the smallest heating energy consumption in Hohhot, Tianjin, and Shanghai reduces the heating energy consumption by 6.00%, 4.82% and 7.69%, respectively. Pareto solution with minimum cooling energy consumption, the cooling energy consumption decreases by 81.25%, 55.33%, 44.44%, and 44.03%, respectively. The objective with minimum lighting energy consumption, 2.88%, 12.50%, 15.38%, and 9.09% energy can be saved in four cities. The optimization range of discomfort hours is relatively small, and the four climatic regions reduced the discomfort hours by 2.00%, 4.63%, 0.87%, and 2.02%, respectively. What's more, it can be seen the energy consumption of heating, cooling, lighting, and discomfort hours is hard to get optimal at the same time. Therefore, it is unwise to pursue the single-objective minimum optimal scheme in most cases, because it is hard to guarantee the requirements of both minimum energy consumption and improved thermal comfort.

5.2. Multi-objective final solution in Pareto solutions

According to some literature research (Delgarm et al., 2016; Bre et al., 2016), people tend to pay the same attention to the objectives of the survey in decision-making. Therefore, the weight coefficients λ_1, λ_2, $\lambda_3\lambda_4$ in Eq. (3) are chosen as $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$, respectively. It should be mentioned that the heating energy consumption in Guangzhou is zero, so the weight coefficients of λ_1, λ_2, $\lambda_3\lambda_4$in Guangzhou are0, $\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$, respectively. In this condition, the optimal design parameters in four cities can be seen in Table 11 and the comparison between optimal solution and base case can be seen in Table 12.

It can be seen from Table 11, under the equal weight of each objective, the optimal configuration of the window in Shanghai and Guangzhou cities are the same, they are Clear_3mm, Argon_13mm, and LoE_Spec_Sel_Tint_6mm. In Hohhot, the optimal configuration of the window is Clear_3mm, Air_13mm, and LoE_Spec_Sel_Clear_6mm. In Tianjin, the optimal configuration of the window is Clear_3mm, Argon_13mm, and LoE_Spec_Sel_Clear_3mm. The performance parameters of the window are shown in the dotted box in Table 11, including SHGC, direct solar transmission, light transmission, and U-value. It can be seen from the performance parameters of the window that the SHGC, solar direct transmission, and lighting transmission in Hohhot and Tianjin are higher than those in Shanghai and Guangzhou. The main reason is that the heating energy consumption is dominant in the severe cold and cold climatic regions, while in Shanghai and Guangzhou, heat dissipation and ventilation are more important. Windows with high SHGC, direct solar transmission, and light transmission are good for reducing heating load in winter. Therefore, windows with high SHGC, direct solar transmission, and light transmission are more recommended for severe cold and cold climatic regions. In Hohhot, the optimal orientation and installation angle of shadings are 0° and 120°, respectively, and the optimal depth of shadings in Hohhot is 0.85 m. In Tianjin, the optimal orientation is 0° and optimal shadings configuration is an installation angle of 110° and depth of 1.00 m. In Shanghai, the optimal parameter of orientation is 0°, shadings installation angle of 110° and depth of 0.4 m, respectively. In Guangzhou, the optimal results are orientation of 270°, shadings installation angle of 110° and shadings depth of 0.7 m, respectively.

As shown in Table 12, when considering the equal weight of the four objectives. The total energy consumption in Hohhot increased slightly by 1.64%, but the number of discomfort hours decreased by 1.14%. Since multi-objective optimization pursues the simultaneous optimization of four objectives, although the total energy consumption increases slightly, it can also be seen from Table 12 that the cooling energy

Table 12
The comparison of optimal design solution with base case.

	Optimal objective	Optimal	Base case	Diff. (%)
Hohhot	**Heating consumption (GWh)**	3.27	3.00	9.00
	Cooling consumption (GWh)	0.10	0.32	− 68.75
	Lighting consumption (GWh)	0.11	0.104	5.77
	Total consumption (GWh)	3.70	3.64	1.64
	Discomfort hours (h)	3341.5	3380	− 1.14
Tianjin	**Heating consumption (GWh)**	1.72	1.66	3.61
	Cooling consumption (GWh)	0.33	0.60	− 45.0
	Lighting consumption (GWh)	0.118	0.12	− 1.67
	Total consumption (GWh)	2.39	2.60	− 8.08
	Discomfort hours (h)	3294.5	3380.0	− 2.53
Shanghai	**Heating consumption (GWh)**	0.72	0.65	10.77
	Cooling consumption (GWh)	0.44	0.72	− 38.89
	Lighting consumption (GWh)	0.14	0.13	7.69
	Total consumption (GWh)	1.51	1.71	− 11.70
	Discomfort hours (h)	3349.5	3377	− 0.81
Guangzhou	**Cooling consumption (GWh)**	1.05	1.59	–33.96
	Lighting consumption (GWh)	0.13	0.11	18.18
	Total consumption (GWh)	1.40	1.91	− 26.70
	Discomfort hours (h)	3308.5	3367.0	− 1.74

Table 13
The comparison of different schemes.

	Optimal objective	$f_1(x)_{min}$	$f_2(x)_{min}$	$f_3(x)_{min}$	$f_4(x)_{min}$	Final solution	Non-Pareto
Hohhot	**Heating consumption (GWh)**	2.82	3.78	3.54	3.80	3.27	3.91
	Diff. (%)	−27.88	−3.32	−9.46	−2.81	−16.37	—
	Cooling consumption (GWh)	0.23	0.06	0.21	0.071	0.10	0.09
	Diff. (%)	155.56	–33.33	133.33	−21.11	11.11	—
	Lighting consumption (GWh)	0.13	0.19	0.101	0.21	0.11	0.20
	Diff. (%)	−35.00	−5.00	−49.50	5.00	−45.00	—
	Total consumption (GWh)	3.39	4.24	4.07	4.29	3.70	4.42
	Diff. (%)	–23.30	−4.07	−7.92	−2.94	−16.28	—
	Discomfort hours (h)	3375.5	3331.5	3379.5	3312.5	3341.5	3342.0
	Diff. (%)	1.00	−0.31	1.12	−0.88	−0.02	—
Tianjin	**Heating consumption (GWh)**	1.58	2.13	2.00	2.11	1.72	1.76
	Diff. (%)	−10.22	21.02	13.64	19.89	−2.27	—
	Cooling consumption (GWh)	0.50	0.268	0.51	0.270	0.33	0.64
	Diff. (%)	−21.88	−58.13	−20.31	−57.81	−48.44	—
	Lighting consumption (GWh)	0.11	0.21	0.105	0.22	0.118	0.118
	Diff. (%)	−6.78	77.97	−11.02	86.44	0	—
	Total consumption (GWh)	2.41	2.82	2.83	2.81	2.39	2.74
	Diff. (%)	−12.04	2.92	3.28	2.55	−12.77	—
	Discomfort hours (h)	3354.5	3264.5	3359.5	3223.5	3294.5	3351.5
	Diff. (%)	0.09	−2.60	0.24	−3.82	−1.70	—
Shanghai	**Heating consumption (GWh)**	0.60	0.89	0.78	0.90	0.72	0.79
	Diff. (%)	−24.05	12.66	−1.27	13.92	−8.86	—
	Cooling consumption (GWh)	0.66	0.40	0.65	0.45	0.44	0.73
	Diff. (%)	−9.59	−45.20	−10.96	−38.36	−39.73	—
	Lighting consumption (GWh)	0.113	0.207	0.110	0.19	0.14	0.12
	Diff. (%)	−5.83	72.50	−8.33	58.33	16.67	—
	Total consumption (GWh)	1.59	1.70	1.75	1.75	1.51	1.86
	Diff. (%)	−14.52	−8.60	−5.91	−5.91	−18.82	—
	Discomfort hours (h)	3378.5	3351.0	3376.5	3347.5	3349.5	3365.0
	Diff. (%)	0.40	−0.42	0.34	−0.52	−0.46	—
Guangzhou	**Cooling consumption (GWh)**	—	0.89	1.49	0.99	1.05	1.55
	Diff. (%)		−42.58	−3.87	−36.13	–32.26	—
	Lighting consumption (GWh)	—	0.19	0.10	0.18	0.13	0.11
	Diff. (%)		72.73	−9.09	63.64	18.18	—
	Total consumption (GWh)	—	1.30	1.81	1.39	1.40	1.88
	Diff. (%)		−30.85	−3.72	−26.06	−25.53	—
	Discomfort hours (h)	—	3304.5	3368	3299	3308.5	3352.0
	Diff. (%)		−1.41	0.48	−1.58	−1.29	—

consumption in the base model has been greatly improved. In Tianjin, Shanghai, and Guangzhou, the total energy consumption dropped by 8.08%, 11.70%, and 26.70%, respectively, and it can be seen that the total energy saving mainly benefits from the reduction of cooling and lighting energy consumption. Meanwhile, discomfort hours in Tianjin, Shanghai, and Guangzhou decreased by 2.53%, 0.81%, and 1.74%, respectively. Also, the energy saving rate of individual energy consumption is far greater than that of total energy consumption. For example, in Tianjin, Shanghai, and Guangzhou, the energy saving rare of cooling energy consumption is greater than that of total energy consumption, the main reason is that the energy saving rate is the energy reduction divided by energy consumption in base case, due to the total energy consumption is greater than cooling energy consumption, the total energy saving rate is far less than the cooling energy saving rate.

5.3. Comparison of different schemes

In order to verify the effectiveness of the multi-objective method. The solution with the smallest single objective in the Pareto solutions is compared with the final solution, which is determined by the multi-objective weighted sum method, and compared with the non-Pareto solution. The comparison results are shown in Table 13.

It can be seen from Table 13 that in Pareto solutions, the solution that only pursues the smallest single objective has poor performance on other indexes. Such as, the scheme with the minimum heating energy consumption in Hohhot has a higher cooling energy consumption than other schemes. From the comparison between the case with the lowest lighting energy consumption in Tianjin and the non-Pareto scheme, it can be found that multi-objective optimization pursues four objectives to reach a better level at the same time, although its total energy consumption is higher than the non-Pareto solution, and its comfort is also worse than the non-Pareto solution. However, it can be seen that the cooling energy consumption in non-Pareto solution is too large. This also fully reflects the importance of solving problems with multi-objective method, that is, to keep all objective function at a better level. Besides, it can also be seen that for the optimal scheme determined by the weighted sum method, its comprehensive performance is better, showing in the total energy consumption is lower than non-Pareto solution, comfort is also better than non-Pareto solution.

The above Pareto schemes are discussed from single objective minimum and a commonly used decision-making mechanism, which is the put the equal weight to all objectives. In practical applications, different weights according to preferences can be assigned to the above four objective functions, and different optimal solutions can be obtained. Therefore, Pareto optimal solutions obtained after four-objective optimization can provide different optimal solutions according to the preferences of designers.

6. Conclusion

In this paper, an easy-operation, useful and efficient method was proposed to conduct a multi-objective problem, using jEplus + EA and DesignBuilder, which is of great benefit for non-programming designers. This method was used to investigate the optimal configuration of windows and shading system for a typical high-rise office building under four major climatic regions of China. The design parameters include the building orientation, the material of each layer of the double-layer window, and the installation angle as well as depth of overhangs. The configuration of windows and shading system is contradictory to heating, cooling, lighting energy consumption and indoor thermal comfort, which constitute the four objective functions of this optimization study. After 50 iterations, Pareto optimal solutions can be obtained to provide designers with reference and basis for design selection.

The optimization results demonstrate that there is a restrictive relationship between the four objective functions, and the hostile relationship between cooling energy consumption and lighting energy consumption, as well as between lighting energy consumption and discomfort hours, is obvious in the Pareto solutions. It is difficult to maintain the indoor comfortable environment in all zones at the same time for multi-zone buildings with large area windows. However, proper windows and shading configuration still has a positive effect on improving indoor thermal comfort that cannot be ignored. Besides, the optimal potential of lighting energy consumption in the four cities is basically the same.

When considering the equal weight of all objectives. Compared with the base case, the total energy consumption in Hohhot increased slightly by 1.64%, the number of discomfort hours decreased by 1.14%. However, the overall performance of the building has been improved. In Tianjin, Shanghai, and Guangzhou, the total energy consumption dropped by 8.08%, 11.70%, and 26.70%, respectively, and discomfort hours decreased by 2.53%, 0.81% and 1.74%, respectively. If different weight coefficients according to the preferences of designers are assigned to the four objectives, the different schemes can be obtained, which is of great significance to the early design stage of buildings.

In this paper, the research on windows and shading system is mainly based on the consideration of energy consumption and thermal comfort. The further research work can consider the visible light performance, carbon emission performance, cost performance of windows and shading system. Moreover, it can also consider more optimization variables, such as the relevant parameters of building envelope, HVAC setpoint temperature, etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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