

Research Article

Optimization of Daylighting, Ventilation, and Cooling Load Performance of Apartment in Tropical Ocean Area Based on Parametric Design

Jianjian Zhang ¹ and Lin Ji ²

¹Macau Institute of Systems Engineering, Macau University of Science and Technology, Macau 999078, China

²Graduate School of Business, SEGi University, Kuala Lumpur 47810, Malaysia

Correspondence should be addressed to Jianjian Zhang; 1809853nmi30001@student.must.edu.mo

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In tropical areas of China, energy saving is an important part of architectural design, and the energy-saving potential of residential buildings has attracted extensive attention. This paper studies the daylighting, ventilation, and building energy consumption in tropical areas to find out the best energy-saving performance parameters. The building model is established by grasshopper, and the parameters of daylighting, ventilation performance and cooling load are simulated. The octopus plug-in in grasshopper is used to calculate the target value iteratively, so as to find the relative optimal value of multiobjective. Finally, the optimized design value is compared with the initial value. The results show that the refrigeration energy consumption is greatly reduced from 188.20 kWh/m² to 163.02 kWh/m², the Daylight Autonomy (DLA) is reduced from 60.71% to 58.56%, and the ventilation wind speed is increased from 0.62 to 0.63 m/s. It can be seen from the results that although the daylighting objectives was reduced, the cooling energy consumption is greatly reduced, and the optimized daylighting layout is more balanced and reasonable. Therefore, on the basis of reasonable layout, this optimization study effectively reduces the refrigeration energy consumption and achieves the goal of green energy saving.

1. Introduction

Since the first energy crisis broke out in the 1970s, the world has paid more and more attention to energy and environmental issues. Among them, building energy consumption accounts for a larger proportion of the global energy consumption. In recent years, with the rapid development of China's urbanization, the rapid urbanization has driven the sustainable development of the construction industry. The urbanization rate of China's urban population has increased from 37.7% in 2001 to 60.6% in 2019. Since 2014, the annual completed area of China's civil buildings has been basically stable at more than 4 billion square meters, and the total construction area in 2019 has reached 64.4 billion square meters. According to the accounting results of energy consumption and emissions of China's construction sector

by the Building Energy Conservation Research Center of Tsinghua University, in 2019, China's construction and operation energy consumption account for 33% of the total energy consumption of the whole society, which is close to the global proportion [1]. Therefore, optimizing building energy-saving design to reduce building energy consumption has become a measure to deal with the increase of total energy consumption in China. In the research direction of building energy saving, scholars have the most research on energy consumption, followed by indoor light environment and building cost. Therefore, the research in this area should be given high attention.

The research on objective optimization and optimization algorithm has been increasing since the late 1990s, and it is common in recent years [2]. Generally speaking, due to the mutual influence and restriction of optimization objectives

in practice, most research studies consider multiobjective optimization problems [3,4]. At the same time, there are many methods to solve the multiobjective optimization problem, among which multiobjective genetic algorithm is often used in the field of building energy saving [5,6]. And, more specifically, when scholars use genetic algorithm to optimize energy consumption and daylighting, but scholars choose different independent variables [7]. Shahbazi et al. [8] used the simulation parametric design model to optimize the daylighting and thermal performance of office buildings by adjusting and optimizing window-to-wall ratio (WWR), window number, window height, and sill height. Mahdavinejad and Mohammadi [9] used to control the louver angle, width, and distance from facade to achieve the purpose of effective daylight illumination and energy consumption close to the optimal solution. Bakmohammadi and Noorzai [10] adopt the multiobjective optimization method to meet the requirements of daylight, comfort, and energy efficient utilization of primary school classrooms by optimizing the characteristics of building orientation, wall inclination angle, window number, WWR, and glazing material. Some scholars have studied the energy consumption and cost objectives. For example, Wang et al. [11] took the total life cycle cost (LCC) and life cycle environmental impact (LCEI) of buildings as objective functions and optimized the building orientation, window type, size, envelope material, and construction variables with the help of MOGA algorithm. Wright et al. [12] used NSGA-II optimization algorithm to optimize the window wall ratio, window height, and other design parameters to achieve the two objective functions of minimum energy consumption and total cost. Some scholars have studied the energy consumption and thermal comfort [13,14]. Yu et al. [15] used the improved multiobjective genetic algorithm to optimize the energy consumption and indoor thermal comfort; then, he established the GA-BP network model to quickly predict the energy consumption and indoor thermal comfort of energy residential buildings and established the multiobjective optimization model of architectural design. Other authors focus on other aspects of research [16–19]. Jalali et al. [20] used genetic algorithms and sustainable methods to optimize the facade of the office building so that the building meets the available space, reduces the heat load, and improves the natural light in the building. This approach helps designers have a more sustainable approach. Zhang et al. [21] used MOGA to optimize the three targets of solar radiation, space efficiency, and shape coefficient to generate a Pareto boundary, which helps the designer to determine the optimal solution.

The above passive building energy-saving design method has changed the design process of architects relying on design experience. With the realization of building energy-saving optimization, designers can obtain more reasonable and energy-saving design scheme of the residential building window wall. However, the above studies usually choose building energy consumption, daylighting, thermal comfort, cost, and other related performance on the optimization objectives. However, few scholars consider ventilation, daylighting, and energy consumption together. In fact,

building natural ventilation is a method to adjust the indoor environment. It can not only adjust the indoor temperature and reduce energy consumption but also improve the indoor air quality and indoor thermal environment. Therefore, natural ventilation should be fully considered in the building design. With the emergence of butterfly in building software grasshopper, it is feasible and necessary to take ventilation as a goal for multiobjective optimization. Therefore, this paper analyzes the daylighting, ventilation, and energy consumption together to form a multiobjective optimization problem, and then, it uses rhino and grasshopper to build a building parametric modeling platform for simulation, and it uses the genetic algorithm in grasshopper for optimization operation.

2. Mathematical Models

2.1. Research Framework. The three optimization objectives are to maximize daylight autonomy (DLA) and ventilation and minimize refrigeration energy consumption, so as to select the best balance of daylight, ventilation, and refrigeration performance. Generally, grasshopper is software that runs computing in rhino environment. Ladybug and Honeybee plug-ins are important computing platforms in grasshopper [22,23]. In this study, Ladybug and Honeybee are used to simulate the daylighting, ventilation performance, and cooling load of buildings, and the genetic algorithm (GA) encapsulated in the plug-in is used to complete the optimization. If the optimization does not meet the requirements, octopus will automatically return and adjust the value of the next design variable, and the simulation will continue until the requirements are met.

The optimization process of building performance is shown in Figure 1. In the first step, the optimization target is determined according to the use function; based on the tropical area, this paper constructs the optimization model with energy consumption, daylighting, and ventilation performance as multiobjective. In the second step, the simulation models of each target are established, and the material parameters of the refrigeration energy consumption model and the daylight model are set. The third step is to determine the decision variable WWR and set the variable range according to the goal. In the fourth step, the parametric modeling method is used to simulate the model to obtain their respective results. In the fifth step, the genetic algorithm in grasshopper octopus plug-in is used to iteratively optimize three target values to generate the Pareto optimal solution set. Finally, the optimal solution is selected from the solution set.

2.2. Location and Climate of Case Building. The research object is located in the southeast of Sanya campus of Hainan Tropical Ocean University. The project consists of four 14-storey apartment buildings, one floor underground, and 14 floors above ground. Because it takes more time to study the daylighting, ventilation, and energy consumption of the whole building, this paper takes the 12th floor of an apartment as the standard floor for objective optimization

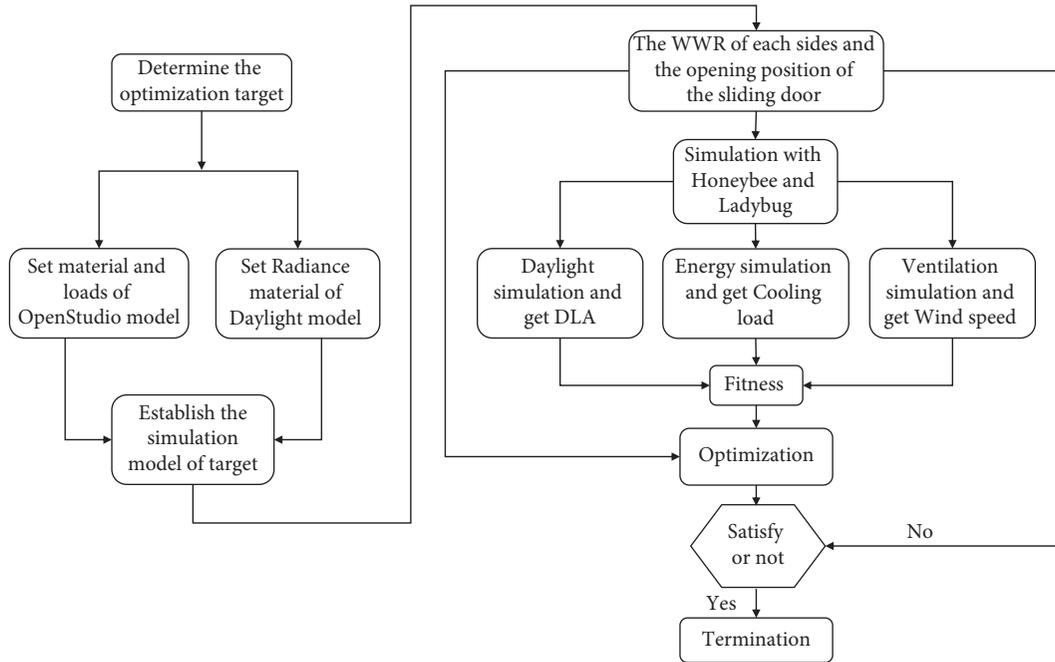


FIGURE 1: Multiobjective optimization process based on simulation.

and studies the variables such as WWR in four directions of the floor. The details are shown in Figure 2.

The building energy-saving design needs to be based on the local climate and environment information, and the research project is located in Sanya, Hainan Province, which belongs to the tropical ocean monsoon climate, so the design should consider the summer high-temperature factors throughout the year. This paper analyzes the outdoor dry bulb temperature of Sanya based on climate information data of Sanya, but because the meteorological database of the U.S. Department of energy does not have the climate information of Sanya, while the climate information of Dongfang is in the information database, which is only 168 km away from Sanya, so it was selected as the reference. The local residents are mainly uncomfortable with high temperature. The annual average temperature is 25.23°C, and the annual average relative humidity is 78.19%. The number of hours below 18°C accounts for 9.20% of the whole year and the number of hours above 26°C accounts for 49.06%. It can be seen from Figure 3 that the annual temperature distribution is basically in summer, so this paper focuses on reducing the refrigeration energy consumption.

2.3. Daylight, Wind, and Energy Modeling and Optimization

2.3.1. Objective Functions. The concept of DLA was originally derived from a design code in Switzerland [24]. In equation (1), DLA is calculated in hours as the basic time unit, and there are 8760 hours in 365 days a year, where T_E is the accumulated hours when the illuminance exceeds the illuminance threshold (300LX) [25]. So, the DLA refers to the percentage of time during the active occupancy hours

that the test point receives more daylight than the illuminance threshold [26,27]:

$$DLA = \frac{T_E}{8760} \times 100\%. \quad (1)$$

Because the building is located in the tropical marine monsoon climate area, the dominant wind direction in summer is south wind, its frequency accounts for 5.43%, and the average wind speed of the dominant wind direction is 4.44 m/s; the flow field distribution of the project is relatively uniform, and the ventilation conditions in the area are good. Therefore, this paper uses the typical outdoor wind speed and direction in summer as the data and uses the butterfly plug-in to simulate the outdoor ventilation. It selects the visual section for the height of the 12th standard floor and then brings the corresponding outdoor wind speed and direction into the indoor window position for indoor ventilation optimization calculation. Figure 4 shows the plane distribution of outdoor wind speed after calculation. The building energy consumption includes four parts, the heating load of the building is zero, and the equipment load and lighting density are set as fixed values. Therefore, this paper only takes the cooling load as the research goal of energy consumption [28].

Therefore, the goal of this paper is to minimize the cooling load and maximize the DLA and wind speed. This paper does not consider the calculation of the equipment room and staircase of the apartment. The octopus calculator can only perform the minimization operation, and it is sufficient to add a negative sign in front of

$$\min \begin{cases} -f_{DLA}(x)(a), \\ -f_{wind\ speed}(x)(b), \\ f_{cooling\ load}(x)(c). \end{cases} \quad (2)$$

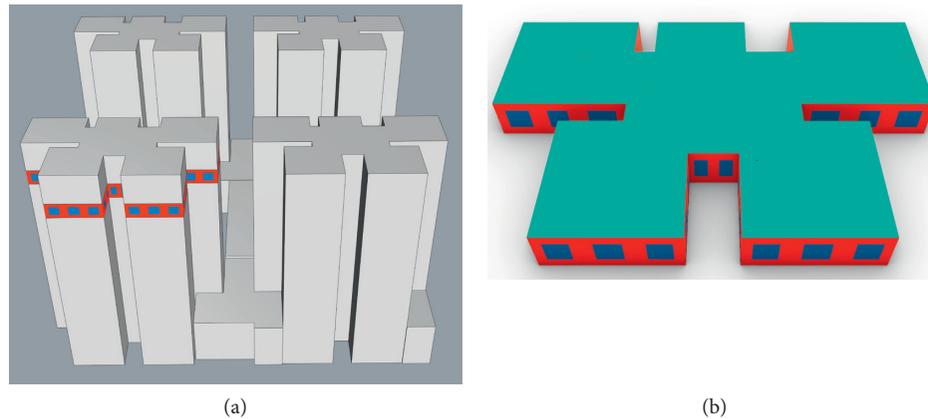


FIGURE 2: The model of apartment buildings. (a) The model of four apartment buildings. (b) Elevation layout of the 12th floor.

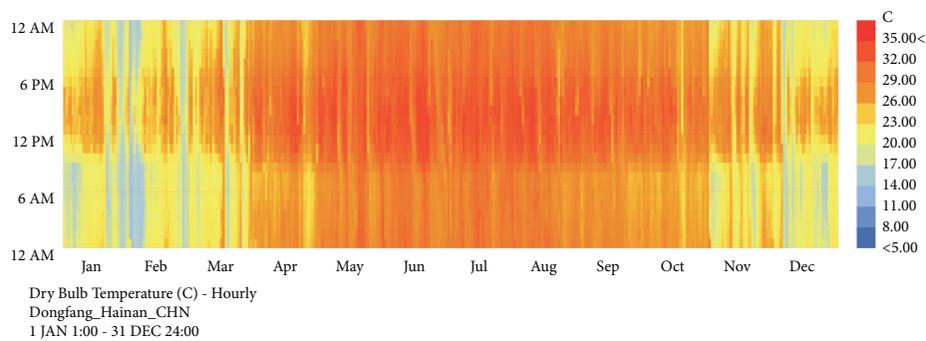


FIGURE 3: Annual dry bulb temperature of Sanya.

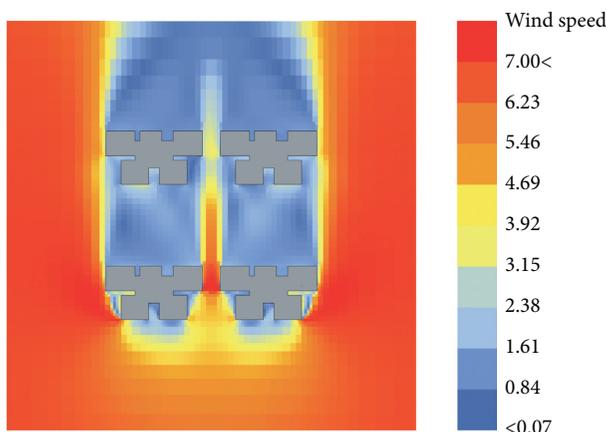


FIGURE 4: Visualization in outside ventilation.

2.3.2. Constraint and Variable. The location and size of building windows have a great influence on building performance. The building window variables in this study include the WWR of the north, west, south, and east sides. In this paper, the parametric modeling method is used to model the apartment and determine the size of the window. It is based on the constraint range of WWR. The purpose of this paper is to get a more comprehensive analysis target value. It is necessary to consider the value range of WWR. Therefore, the upper limit of WWR can be considered with reference to

the design standard for energy efficiency and green residential building in Hainan [29], so the single facade WWR should not be greater than 0.40, and the minimum WWR should not be less than 0.1, and the specific change values are shown in Table 1.

3. Simulation Parameter Settings

Because the real material and the assumed material have the same total thermal resistance, this study does not pay attention to the changes of the wall, floor, and other building envelope structure, but it should consider the size of the building window. Therefore, a simplified method is adopted to assume that the multilayer material of the opaque building envelope is a single material. This paper selects (6 clear_12 air_6 clear) glass as window material [30]. The material information of the EP structure is shown in Table 2. Among them, the wall and ceiling of the apartment choose white latex paint, and the floor chooses white marble structure as their indoor radiation material.

On the threshold of energy region parameters, because Sanya is located in the tropical region, only the cooling demand is considered, and the cooling temperature is set at 26°C; the equipment load is set at 14 W/m²; at present, energy-saving lamps are more common, so the daylighting density is set at 5 W/m²; the number of people in each area is set to 0.04. The details are shown in Table 3.

TABLE 1: Design variables of 12th floor windows.

Type	Material	Parameter	Range
WWR of north window	6 clear_12 air_6 clear	X_1	[0.1, 0.4]
WWR of west window		X_2	[0.1, 0.4]
WWR of south window		X_3	[0.1, 0.4]
WWR of east window		X_4	[0.1, 0.4]

TABLE 2: Materials of EP construction.

Parameter	EP no. mass opaque material Exterior wall	EP transparent material 6 clear_12 air_6 clear
R-value ($\text{m}^2\cdot\text{K}/\text{W}$)	1.20	
U-value ($\text{W}/\text{m}^2\cdot\text{K}$)		2.59
Thermal solar heat gain coefficient (SHGC)		0.75
Visible transmittance (VT)		0.81

TABLE 3: Zone energy parameter.

Member	Parameter	Value
EP zone loads	Equipment load (W/m^2)	14
	Light density (W/m^2)	5
	Number of people (ppl/ m^2)	0.04
EP zone thresholds	Cooling set point ($^{\circ}\text{C}$)	26
HVAC system	PTAC	

Because this paper chooses the residential buildings located in the university campus as the research object of energy saving, so the cooling mode of the HVAC system is PTAC [31]. At the same time, considering the accuracy of energy consumption calculation, it is necessary to properly refer to the working and rest time of residents, so the occupancy schedule is introduced to divide the working and rest time of the whole year. In China, the annual working hours are from 8 am to 6 pm, and the absence of teachers during the National day and Spring Festival holidays is also taken into account. In Figure 5, the red area is 1, which indicates the time period when residents are at home, the yellow area is 0.5, which indicates the time period when residents are at home or not at home, and the blue area is 0, which indicates the period when the residents are not at home. From Figure 5, it can be seen that the probability of staying at home during the rest time in the evening and most of the weekend is 1, the probability of staying at home during the working time is 0, and the probability of staying at home during the commuting time is 0.5. Such a detailed design is to reasonably calculate the energy consumption time and provide a more scientific basis for energy saving.

4. Multiobjective Optimization Results and Discussion

4.1. Multiobjective Optimization Results. In the interface, parameter settings of Octopus plug-in was shown in Table 4. The model takes 5 days in the process of multiobjective optimization, and after 35 generations of calculation, 433 feasible solutions are obtained. When the three optimization objective values tend to be stable, it shows that they are

convergent enough. In the three-dimensional coordinate system, the three axes represent DLA, wind speed, and cooling load, respectively. As shown in Figure 6, the Pareto optimal solution including the 35th generation non-dominated solution set is obtained.

Regarding the numerical distribution range of the nondominated solutions of DLA, the cooling load and ventilation have the widest range of values, the cooling load from 132.57 to 265.08 kwh/m^2 , and the ventilation volume from 0.38 to 0.88 m/s , and the smallest distribution range is DLA, which is from 53.67% to 66.68%. This data shows that, in the process of building optimization, building decision variables have a great influence on cooling load and ventilation. Therefore, the building WWR should be appropriately adjusted according to the optimization goal in the design. All aspects of the optimized design can create better indoor daylighting and ventilation capabilities and can effectively reduce building energy consumption.

4.2. Correlation between Goals. The relationship between DLA and energy consumption is shown in Figure 7. It represents the nondominated solution set of cooling load and DLA in the 35th iteration. It is obvious that the performance of DLA is negatively correlated with the cooling load. When DLA increases from 53.67% to 66.68%, the cooling load will increase from 132.57 to 265.08 kwh/m^2 . The increase in DLA is due to the increase in WWR, which improves daylighting performance; but at the same time, the larger WWR will lead to the increase of cooling energy consumption. Therefore, DLA and cooling load should be considered simultaneously in the optimization process to obtain the relative optimal value.

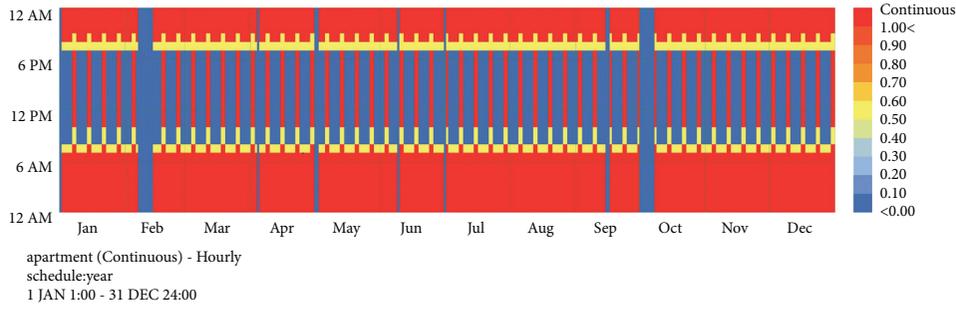


FIGURE 5: Annual occupancy chart for the apartment.

TABLE 4: Interface parameter settings.

Interface parameter	Elitism	Mut. probability	Mutation rate	Crossover rate	Population size
Value	0.5	0.05	0.1	0.8	10

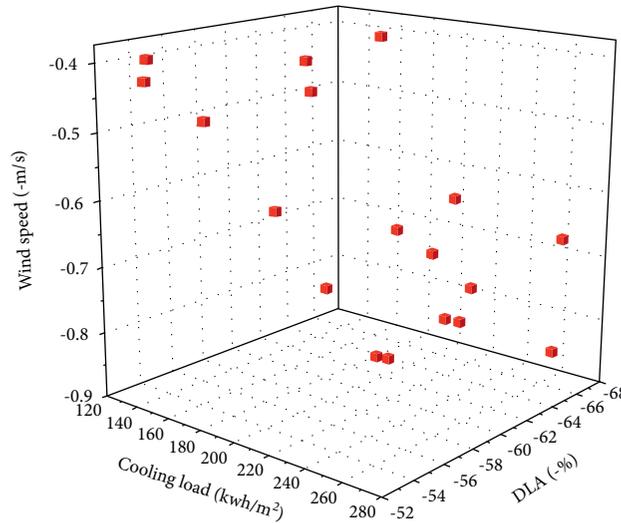


FIGURE 6: Nondominated solutions in the 35th iteration.

The relationship between DLA and ventilation performance is shown in Figure 8. When the DLA ratio increases from 53.67% to 66.68%, the wind speed is changed largely with the increase of DLA in the initial stage, but in the middle and later stages, the wind speed is relatively stable. This is because when DLA is at a very low stage, the WWR of all windows is very small, and the ventilation effect is very poor, so the ventilation is greatly affected by the size of the window. With the increase of DLA, the corresponding WWR will increase appropriately, the opening of windows is conducive to ventilation, and the ventilation is at a higher value and does not change much. The two objectives are positively correlated on the whole.

The relationship between ventilation performance and energy consumption is shown in Figure 9. When the cooling load decreases from 265.08 to 132.57 kwh/m^2 , the ventilation changes in a certain range in the initial stage, but in the middle and later stages, the wind speed decreases with the decrease of energy consumption. This is because when the indoor energy consumption is in the range of 190 to

265 kwh/m^2 , the corresponding WWR value is still large, which is still conducive to natural ventilation and has little effect; when the indoor energy consumption is in the range of 130 to 190 kwh/m^2 , the WWR is further reduced, and the air vent is smaller; the ventilation is greatly affected, and it shows a decreasing trend with the reduction of energy consumption. So, we should also consider a factor of interaction in the optimization.

From the comparative analysis of the above three objectives, it is concluded that DLA and cooling load are negatively correlated, DLA and ventilation are positively correlated on the whole, and ventilation and cooling load are negatively correlated on the whole. Therefore, in the process of the design, we need to consider all design goals.

4.3. Comparison between Optimal Solution Set and Initial Plan. Three relatively optimal nondominant solutions are selected from the 35th generation, which can achieve better building performance goals. Table 5 lists the relative optimal

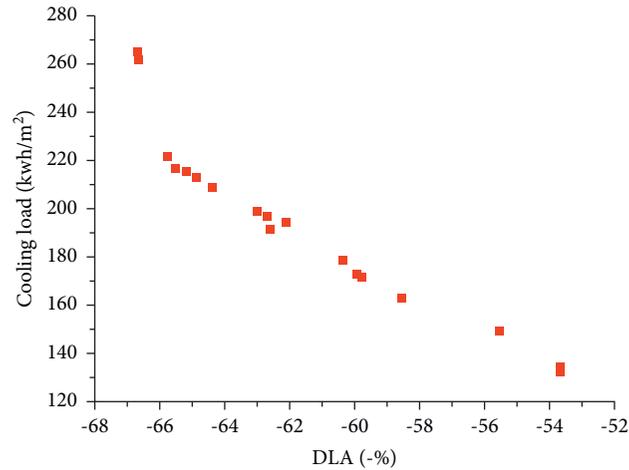


FIGURE 7: The cooling load and DLA performance of nondominated solutions in the 35th iteration.

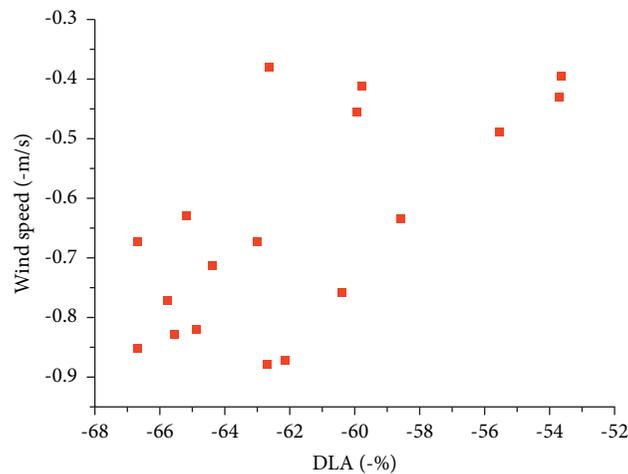


FIGURE 8: The DLA and ventilation performance of nondominated solutions in the 35th iteration.

solutions and corresponding decision variables of the three options. It can be seen that, in the initial plan of the building, the cooling load value is also higher and the DLA and the wind speed is moderate. The independent variables of the initial plan design are significantly different from those of the relative optimal solution, but the values of the relative optimal solution are relatively similar. The corresponding design model is shown in Figure 10. Compared with the initial plan, cooling load is changed from 188.20 kwh/m² to 163.02~198.76 kwh/m², the wind speed of ventilation is increased from 0.62 m/s to 0.63~0.76 m/s, and the value of DLA changed slightly from 60.71% to 58.56%~62.99%. The DLA values of the three relative optimal solution sets were all above 50%, and it still had a very good daylighting.

In terms of daylighting, this paper selects three relatively optimal nondominant solutions option 1 and makes a comparative analysis with the initial plan. The DLA of the initial plan and option 1 are calculated, respectively, by using daylight simulation, and they are visualized, respectively, as shown in Figure 11. The DLA of the initial plan in Figure 11(a) is 60.71% and that of option 1 in Figure 11(b) is

58.56%. It is found that the overall illumination is only reduced by 3.54% after optimization and adjustment. As can be seen from Figure 11, the DLA values of the north, east, and west sides of the whole floor decrease slightly. This is due to the decrease of WWR in these three directions, but the overall DLA of this layer has little change after optimization. It can be seen that the optimized layout keeps the daylighting stable.

In terms of ventilation, butterfly is used to simulate the ventilation of the initial plan and option 1, respectively, and the wind speed is visualized, which is shown in Figure 12. In Figure 12(a), the average wind speed of the initial plan is 0.62 m/s, and in Figure 12(b), the average wind speed of option 1 is increased to 0.63 m/s. Although the overall wind speed does not increase much, but the optimization makes the overall ventilation distribution of the floor uniform and reasonable; especially, in the public passage, the ventilation effect is remarkable and can meet the requirements of natural ventilation; it can be seen that the optimized independent variable value is conducive to room ventilation. This paper optimizes the wind environment for the standard

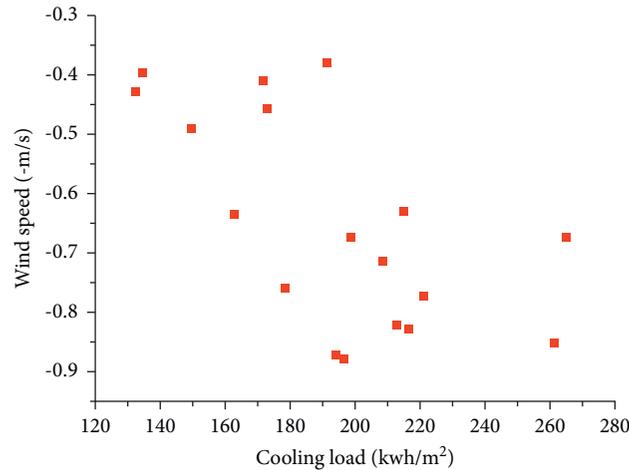


FIGURE 9: The cooling load and ventilation performance of nondominated solutions in the 35th iteration.

TABLE 5: A comparative analysis of Pareto optimal solutions and the initial plan of the apartment.

Room style	X_1	X_2	X_3	X_4	Cooling load (kWh/m ²)	DLA (%)	Ventilation (m/s)
Initial plan	0.20	0.20	0.30	0.20	188.20	60.71	0.62
Option design 1	0.13	0.14	0.29	0.15	163.02	58.56	0.63
Option design 2	0.21	0.17	0.29	0.15	178.51	60.37	0.76
Option design 3	0.37	0.14	0.29	0.15	198.76	62.99	0.67

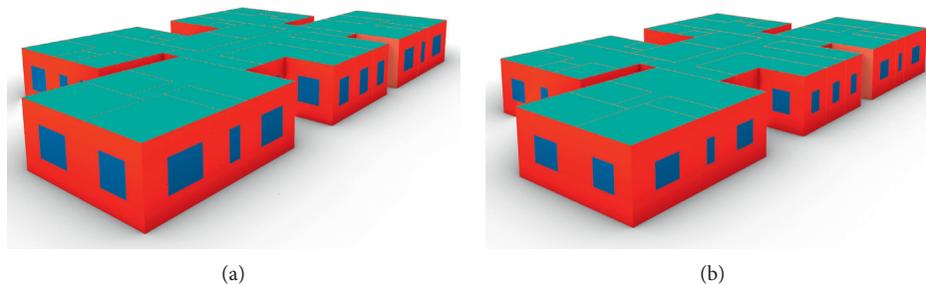


FIGURE 10: The initial plan and optimal solutions. (a) North and east elevations of the initial plan. (b) North and east elevations of the option design 1.

floor of an apartment, but the wind environment of each apartment is different in different directions, so the optimized independent variable parameters are only used as a reference for this apartment and are not applicable to the other three apartments.

In terms of energy consumption, Figure 13 shows the comparison of monthly cooling load before and after optimization. In the initial plan, the annual energy consumption is 188.20 kWh/m², while the optimized energy consumption in option 1 is 163.02 kWh/m², with a decrease of 13.38%; from October of that year to March of the next year, the average monthly cooling load decreased by 14.08%;

from April to September of the same year, the monthly average decline was even lower by 12.90%. It can be seen that the optimization effect is more obvious in winter, so compared with the initial plan, the reduction of refrigeration energy consumption in the whole year has achieved obvious results.

Therefore, through the above analysis, it can be seen that the optimized building achieves a good improvement in energy consumption without affecting the lighting and ventilation conditions, which can effectively realize the optimization of building energy conservation and emission reduction.

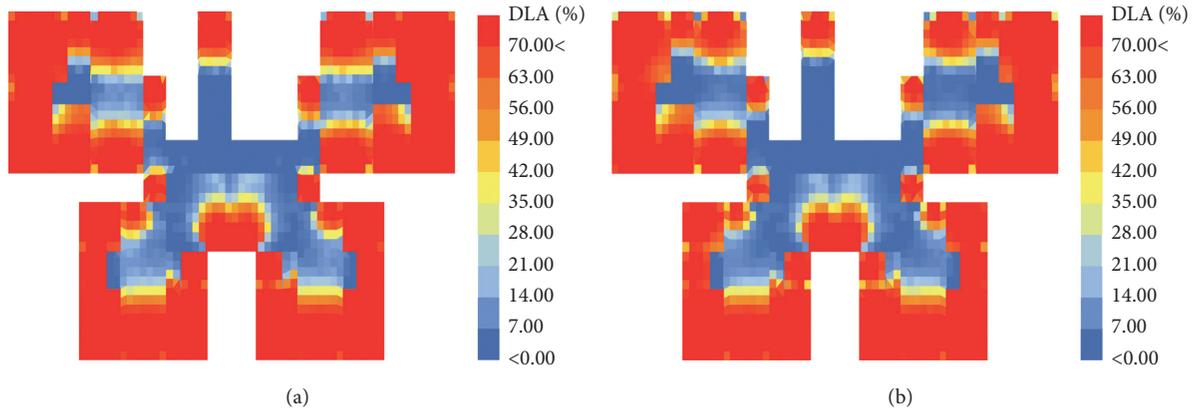


FIGURE 11: Visualization of DLA before and after optimization. (a) DLA of initial plan. (b) DLA of option 1.

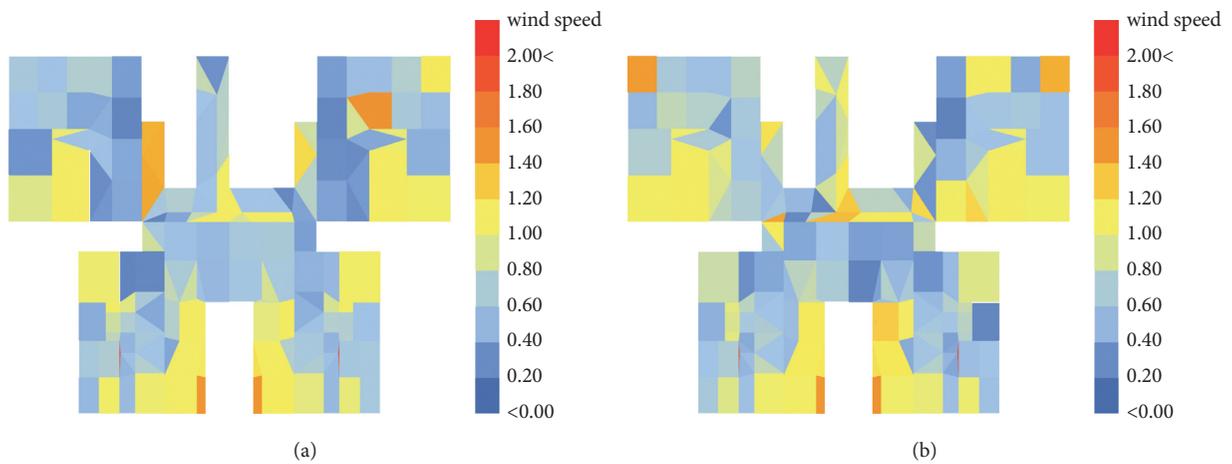


FIGURE 12: Visualization of wind speed before and after optimization. (a) Wind speed of initial plan. (b) Wind speed of option 1.

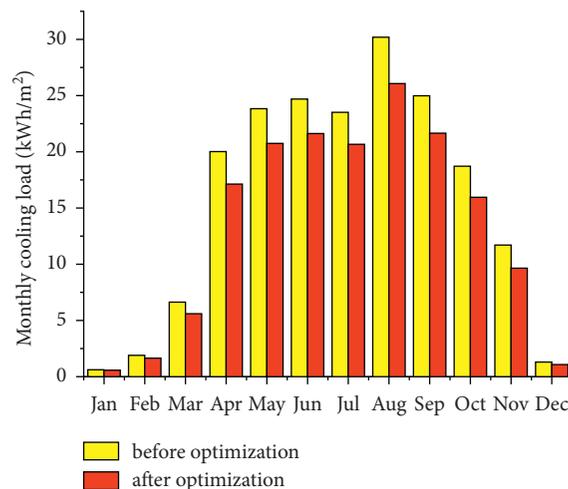


FIGURE 13: Before and after optimization of cooling load.

5. Conclusions

This research is mainly based on the parametric design platform rhino and grasshopper to design and simulate the apartment and focuses on the parameter optimization

problem of genetic algorithm on grasshopper canvas. Taking an apartment in Sanya as an example, through automatic exploration of design, the optimization model of the window opening mode in all directions is realized, and the performance of daylighting, ventilation, and energy is evaluated, so

as to obtain better daylighting level, achieve higher ventilation level, minimize annual cooling demand and to help designers make decisions.

After 35 generations of iterative calculation, the model produces nearly 433 solutions, all of which form the Pareto front of the optimal Pareto curve containing the optimal solution. The relative optimal solution set is found by analysis. Compared with the initial plan, the cooling energy consumption is reduced from 188.20 kWh/m² to 163.02 kWh/m², DLA decreased from 60.71% to 58.56%, the wind speed of ventilation is increased from 0.62 to 0.63 m/s, the reduced daylighting meets the design requirements, and the optimized daylighting and ventilation make the numerical distribution area more balanced and reasonable. Therefore, the optimized independent variable value is reasonable, which coordinates multiple objectives to achieve a relatively reasonable value.

From a practical point of view, considering that Chinese holiday time will have a certain impact on the energy consumption analysis of apartment buildings, this paper introduces the work and holiday arrangement in the energy consumption analysis, so as to calculate the actual energy consumption more accurately. This paper creatively takes the goal of ventilation as the research goal, considers and analyzes it together with daylighting and energy consumption, and forms a multiobjective research. Finally, as the building energy consumption and lighting in Sanya are located in the tropical zone, it has significant characteristics and puts forward some meaningful suggestions for the regional building energy saving and sustainable development.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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