Study on Optimization of Building Climate Adaptive Morphology in Cold Regions of China: Case of U-Shaped College Building

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Abstract. Proper design of building form will facilitate the use of climate environment in order to reduce the reliance of buildings on active equipment. This study takes the cold region of China as the research area, and Jinan city of Shandong province as a typical city in the cold region for specific research. The multi-objective optimization tool based on NSGA-II algorithm is used to optimize the opening angle, length of both sides and floor height of the building, and finally the optimal size range of the university teaching building under the influence of solar radiation heat gain in winter and summer is obtained, and the results show that for the U-shaped university teaching building, the parameters that affect the building performance more in the case of the east side opening are the length of the north side building and the rotation angle of the south side building, and the parameters that affect the performance more in the case of the west side opening are the length of the building on the south side.

Keywords: Solar radiation heat gain · Multi-objective optimization · NSGA-II algorithm

1 Introduction

The cold region is one of the five climate zones in China. It's climate index is: the average temperature of the coldest month 0–10 °C as well as the average daily temperature ≤5 °C for 90–145 days [10]. Cold regions in winter temperatures are low and last for a long time, the lowest temperature can reach minus 20 °C, the summer temperature is generally higher up to 32 °C, the duration of 2 months [9], the sunshine time varies greatly with the seasons, in this case the cold regions need to consume a lot of energy in the winter heating, and the summer need to use air conditioning and other mechanical equipment for cooling, because of the continuous transformation of the climate environment, cold regions each year need to consume a lot of energy to improve the thermal environment, how to improve the status quo has become a problem that needs to be solved. Jinan City,

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Shandong Province, located at 36°40′N, 117°00′E, in the eastern part of China, belongs to the cold region and has more obvious cold region climate characteristics. In this paper, Jinan City will be selected as a representative city in the cold region for the study.

In Chinese cities, the number and scale of colleges and universities are large (Figs. 1 and 2), which makes the college buildings rely too much on equipment to regulate the building environment, and their energy consumption accounts for a relatively large amount [4]. In view of these, it is urgent to find the best way to reduce the dependence of teaching buildings on equipment and use their own architectural advantages to obtain a suitable building environment.

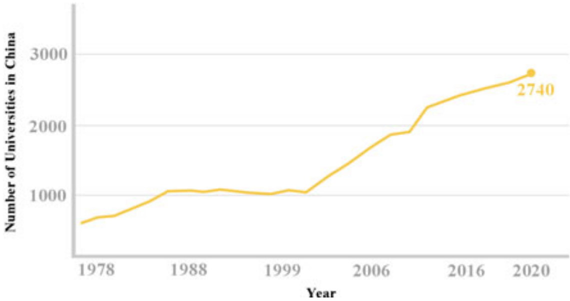


Fig. 1. Number of universities in China

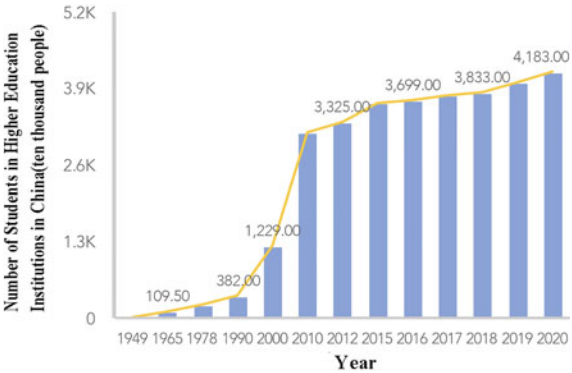


Fig. 2. Number of students in higher education institutions in China

The process of changing the thermal environment of the building due to seasonal changes plays a key role in the solar heat gain of the building, if the building solar heat gain is reduced in summer and increased in winter, it can effectively improve the building thermal environment and reduce the energy consumption required in the later stage. As the interface between the building surface and the outside world, the specific form of the building has a direct impact on the solar heat gain of the building, if we consider the coupling relationship between the solar heat gain of the building and the building form, we can take into account the changes of the building heat gain caused by seasonal changes at the early stage of the building design to maximize the use or avoid the solar heat gain, so as to reduce the energy consumption caused by improving the thermal environment of the building at a later stage and realize the sustainable development of the building.

Many researchers have paid attention to this problem and conducted a series of experiments and explorations. Mustafa did a study on the correlation between building form and solar radiation heat gain for a standard building form of rectangular shape [14]. Kampf Jerome Henri and other scholars applied a new method of predicting daylight radiation to study the morphological and energy-saving design of building forms and neighborhood forms [7]. In 2012, Zerefos and others quantified the difference in energy consumption between different forms of prismatic buildings [18]. After 2015, related scholars optimized the general building layout [15], building morphology [1, 12], and building details [13] with the goal of building solar radiation heat gain, and obtained a better building thermal environment. From past studies, it can be seen that the building form is closely related to the solar heat gain of the building, and by optimizing the design of the building form, the solar heat gain of the building can be changed, thus improving the thermal environment of the building.

How to quantitatively optimize the design of building form according to the external environment has become the core problem. In the early days, due to the limitation of technical conditions, researchers could only carry out quantitative design by "trial and error method". This approach is not only inaccurate, random and inefficient, but also requires a lot of time and cost. With the development of computer technology and optimization algorithms, the optimization of buildings can be considered directly from the optimization target, and then the parameters to be optimized can be set and the optimization design can be completed by iterative operation of optimization tools (Fig. 3).

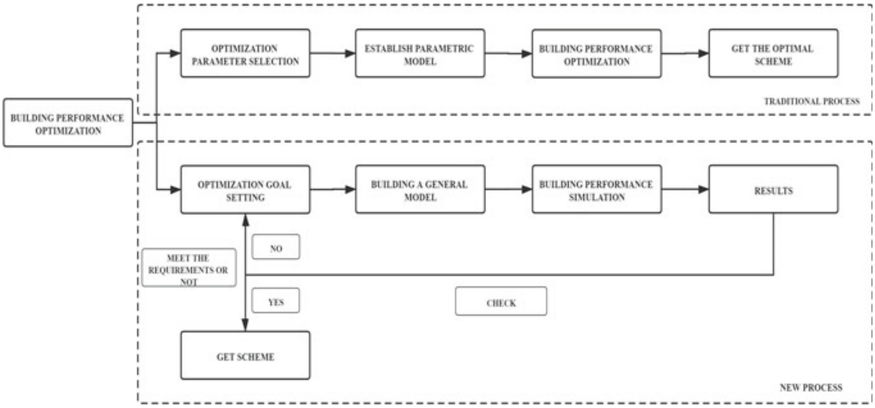


Fig. 3. Comparison of traditional methods and new methods

For this aspect of research, most of the early studies were explored on technical framework [17] and building construction [3], and after 2010, studies were focused on building group form and building form optimization, such as Martins selected typical building layout features in five Brazilian cities and conducted a multi-objective optimization study on the morphology of building clusters based on solar radiation heat gain [8], Longwei Zhang adjusted the morphology for freeform buildings in cold and severe regions represented by Shenyang, driven by several optimization objectives such as daylight radiant heat gain, volume coefficient, and space efficiency [19].

However, most of the existing studies are focused on single-objective optimization, and the optimization of multi-objective mainly considers the influence of different environmental elements, lacking the consideration of the influence of environmental elements on the research subject due to time change, which leads to the existing research subject can only consider the situation in a certain time period, and it is difficult to take into account the environment of other time periods in the region. For buildings that are used by a large number of people for a long period of time, it is necessary to consider the differences in solar heat gain of the buildings due to seasonal changes, and to make full use of or avoid the solar heat gain of different seasons, so as to reduce the energy required to improve the thermal environment of the buildings in the later period. The purpose of this paper is to construct an optimal design method for U-shaped college buildings in cold regions of China, explore the relationship between the optimization objectives, and make specific suggestions.

2 Materials and Methods

2.1 Intelligent Optimization Methods

This paper proposes an intelligent design method for building form optimization based on solar heat gain in an attempt to improve the thermal environment of university buildings in cold regions (Fig. 4). The goal of the optimization is to optimize the solar heat gain of the building so that the building has more solar heat gain in winter and less solar heat gain in summer. This process includes several steps such as determining morphological parameters, model construction, morphological optimization, and analysis and processing.

2.2 Optimized Objects

This paper selects the teaching building in the cold region of China as the research object. In the cold regions of China, due to the constraints of climate conditions, design specifications and functional requirements, there are three main types of college buildings in terms of overall layout, namely: one-way type, combined type and centralized type, and the one-way type can be divided into one-way type, U type, L type and H type (Fig. 5).

U-shaped teaching buildings are widely used, highly applicable and influenced by solar radiation, so this paper chooses one type of U-shaped teaching buildings for in-depth study. Through the research of U-shaped college buildings in cold areas, it is found that the main function distribution is linear, and the building blocks facing the opening of the U-shaped building are mostly facing east or west because of the number of classrooms, and the function is mostly small classrooms for small group teaching or

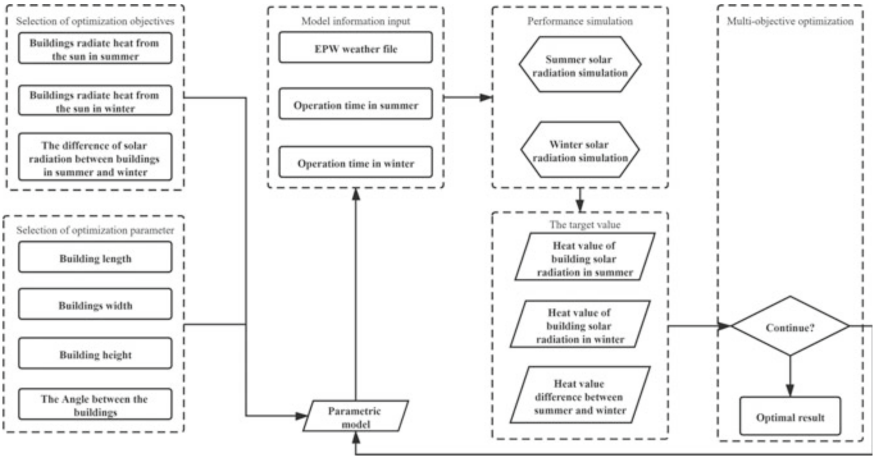


Fig. 4. Intelligent design method of building form optimization

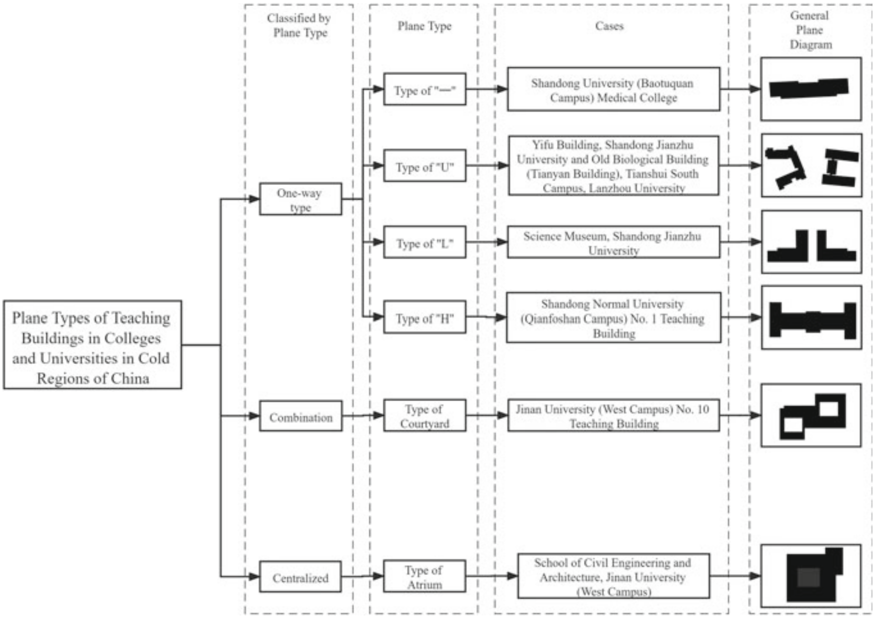
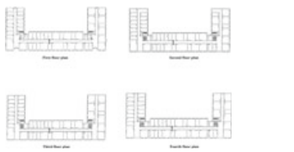
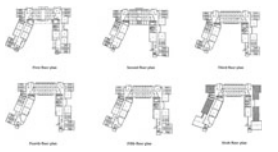


Fig. 5. Classification of colleges and universities in cold regions of China

students' self-study, and the building blocks on both sides of the opening are mostly arranged in the south and north as the main classroom. Besides, the multi-functional classrooms are usually set at the end of the corridor, and the number of symmetrical arrangement is usually two (Table 1).

Table 1. Cases of academic building plan

Old biological building (Tianyan building), Tianshui South Campus, Lanzhou University	Yifu Building, Shandong Jianzhu University	Molecular Science Innovation Platform, Institute of Chemistry, Chinese Academy of Sciences
		

2.3 Optimized Goals

In this paper, we focus on the problem of solar radiation heat gain of buildings caused by seasonal changes, so the optimization objectives are solar radiation heat gain of buildings in winter and solar radiation heat gain of buildings in summer, and in order to consider the influence of the two objectives on the optimization results and avoid the situation that the optimization results are excessively biased to one side, we need to add a third objective: the difference between solar radiation heat gain of buildings in summer and solar radiation heat gain of buildings in winter, and by adding this objective, we can consider the influence of the previous two on the results.

2.4 Optimizing Variables and Constraint Ranges

For U-shaped buildings, the length and height of the building and the angle of the building openings determine the building form and also affect the solar heat gain of the building, so these variables need to be set specifically (Fig. 6).

2.4.1 Building Length

According to the results of the above research and related data collection, the main functions of U-shaped college buildings in China are usually arranged in the building blocks on both sides of the openings, while the blocks facing the openings are often small classrooms with some auxiliary functions. The lengths of each side of the building are added up by each classroom, so the total length can be set by setting and adding up the lengths of individual classrooms. Classrooms are divided into three main categories according to their functions, namely, regular classrooms, multifunctional classrooms and auxiliary classrooms. According to the requirements of the teaching building and the building modulus, the length of a single general classroom is generally 8.1–9 m with a step length of 0.3 m, and the length of a single multifunctional classroom is 11.1–12 m with a step length of 0.3 m (Table 2), while auxiliary classrooms are not specifically set because they are not within the optimization range (Fig. 7).

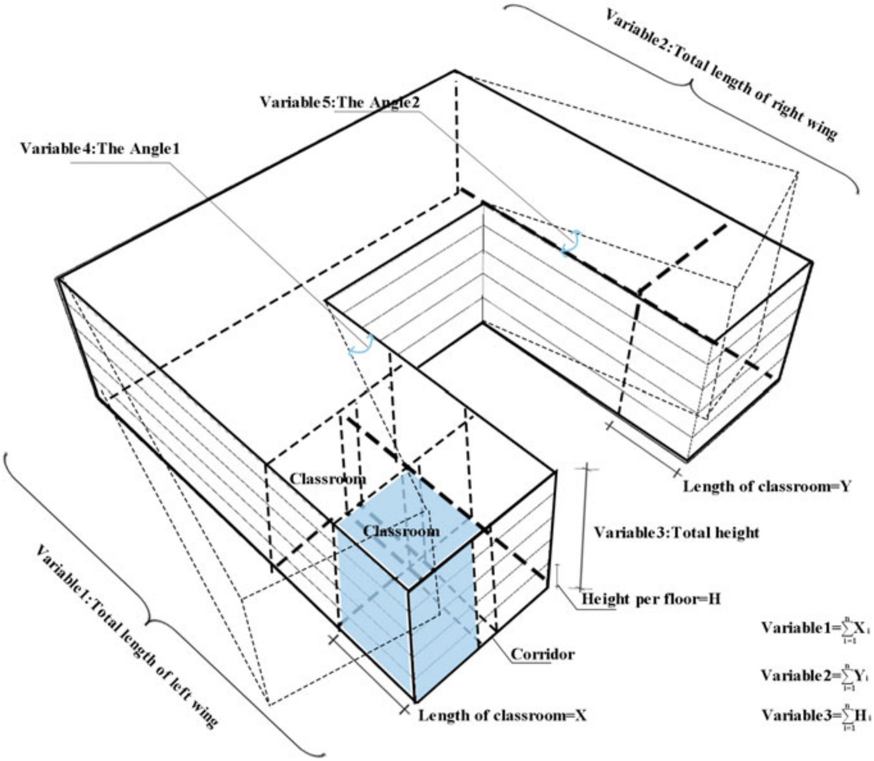


Fig. 6. Graphical representation of building optimization variables

Table 2. The value ranges and the steps of variables

Variables	Unit	Value ranges	Steps
Length of a single general classroom	m	8.1–9.0	0.3
Length of a single multi-purpose classroom	m	11.1–12.0	0.3
Height of each floor of the building	m	3.6–4.5	0.1
North side rotation angle	°	20	1
South side rotation angle	°	20	1

2.4.2 Building Height

The height of each floor is set with reference to the relevant regulations of China for teaching buildings and combined with the current function of classrooms, with 0.1 m as the step, and the range is chosen from 3.6 to 4.5 m.

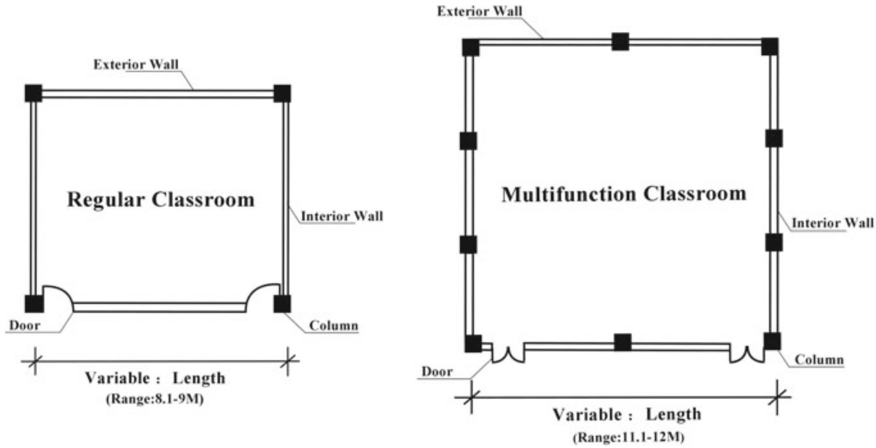


Fig. 7. Single classroom variable setting

2.4.3 Building Opening Angle

The building opening angle affects the shading between buildings and has an important impact on the study of solar heat gain of buildings. The building opening angle is set within a range of 20° for both the north and south sides of the building, taking into account the land use, utilization, and evacuation of the building.

2.5 Dynamic Information Modeling and Optimization Based on Solar Radiation Simulation

The article uses Rhino [11] and Grasshopper [6] platforms to construct dynamic information models, Ladybug plug-in which can be downloaded from the Food4Rhino [5] website to simulate the solar heat gain of buildings by inputting EnergyPlus Weather file (.epw) [2], and the highly visualized Wallacei plug-in [16] to perform multi-objective optimization (Fig. 8).

2.5.1 Reference Building

The reference building is located in a university in Jinan. The plan of the reference building is a U-shaped college building with 135° opening, and its dimensions are 75, 85 and 60 m. The building height is 21.6 m. The floor plan and the initial geometric model of the reference building are shown in Figs. 9 and 10.

2.5.2 Simulation Parameter Setting

In the setting of building parameters, the two wings of the U-shaped building can only be contracted inward in the east–west direction and cannot be extended outward because the whole building is limited by the site area in the east–west direction. As we can see from the plan, there are one multi-functional classroom and four general classrooms in the north block, considering the symmetrical arrangement of the classrooms, only one

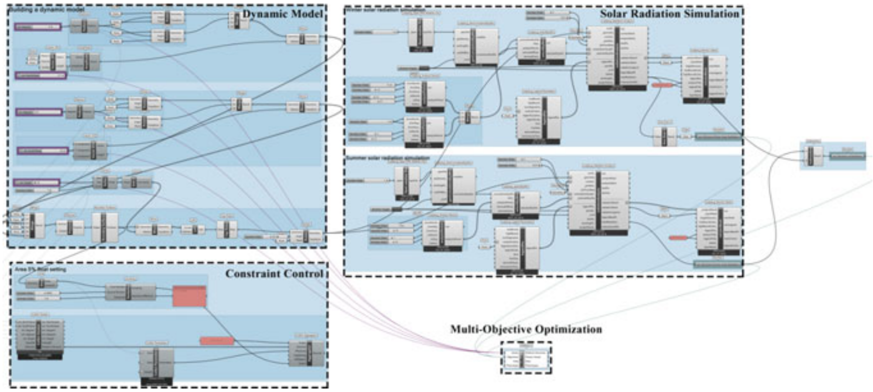


Fig. 8. Operation of optimization and simulation

multi-functional classroom and two general classrooms need to be optimized in terms of length. Therefore, the total optimization range R1 = R (multifunctional classroom) + R (ordinary classroom) * 2 = (12–11.1) + (9–8.1) * 2 = 2.7 m; the south side of the block has a multifunctional classroom and four ordinary classrooms, taking into account the symmetrical layout of the classroom, in the length of only one multifunctional classroom and three ordinary classrooms can be optimized, the optimization step length of 0.3 can be unified to set, multifunctional classroom length measured 12 m, the length of ordinary classrooms measured 9 m, so the total optimization range R2 = R (multifunctional classroom) + R (ordinary classroom) * 3 = (12–11.1) + (9–8.1) * 3 = 3.6 m. Considering the limitation of the site, the final optimized length range for the north side is 57.3–60 m, and the optimized length range for the south side is 71.4–75 m.

In terms of rotation angle setting, the north side building block is rotated 15° to the north and 5° to the south considering the site conditions, with the north side recorded as negative and the south side recorded as positive, while the south side block has a narrow initial state and can only be deflected to the south with a maximum offset angle of 20° and a rotation process step of 1° (Figs. 11 and 12). The height of each layer of the building is used as the optimization parameter, and the value is set with reference to the relevant national regulations for teaching buildings and the current function of the classroom, with 0.1 m as the step, the range is 3.6–4.5 m, and the number of layers is set as the initial state. The buildings in the site are arranged with openings to the west (Table 3). According to the above research results, the openings of buildings in cold regions of China can be to the west or to the east, and in order to increase the generality of the optimization experiment, it is necessary to discuss the typical building as an example in two cases of east and west openings respectively.

2.5.3 Solar Radiation Heat Gain Simulation

In the parameter setting of solar radiation simulation, the grid size of solar radiation calculation is chosen to be 2 m * 2 m with relatively high accuracy, and the grid offset distance of the test point is set to 0.01. By connecting to the CSWD climate database,

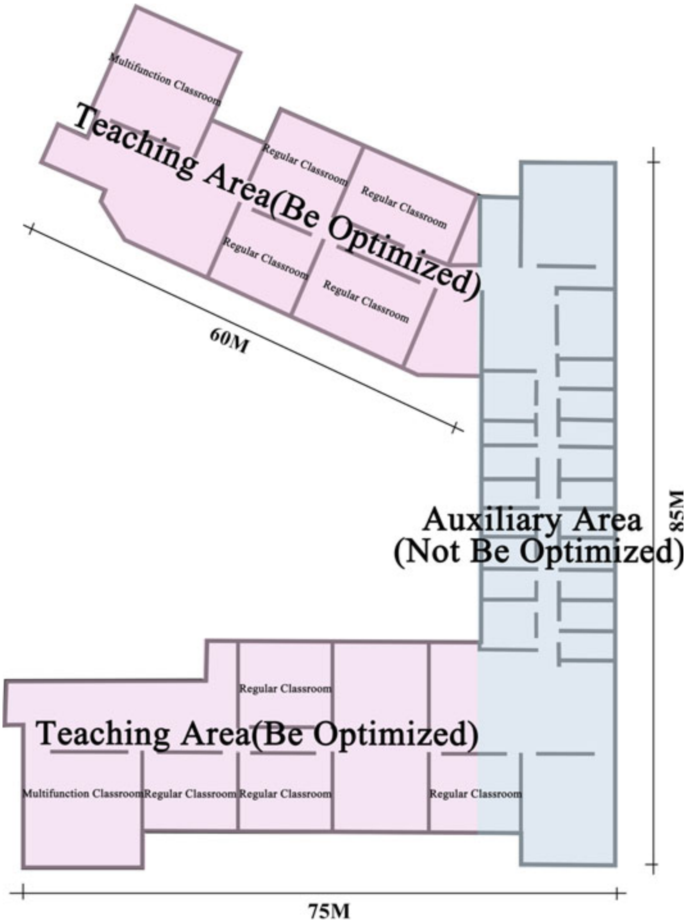


Fig. 9. Reference building plan

the solar heat gain of the building can be simulated for different time periods (Figs. 13, 14, 15, and 16). Considering that the subsequent optimization is based on the genetic algorithm and can only be optimized in the direction of the minimum value, the final solar radiation results in winter are taken as the reciprocal.

2.5.4 Multi-objective Optimization

The whole operation process is based on genetic algorithm (NSGA-II), and the size of each population generation is set to 20, the number of generations of simulated population is set to 100, the crossover rate is set to 0.9 in the genetic algorithm, and the variation rate keeps the default value (Table 4).

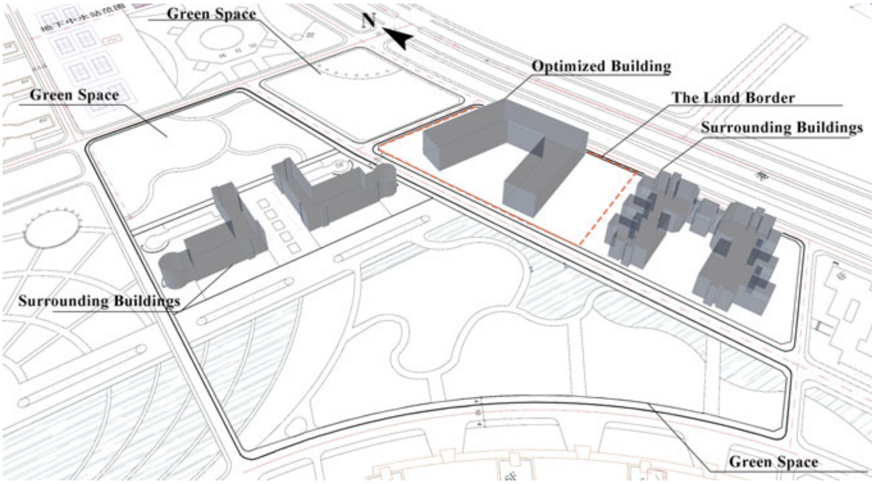


Fig. 10. Reference building location

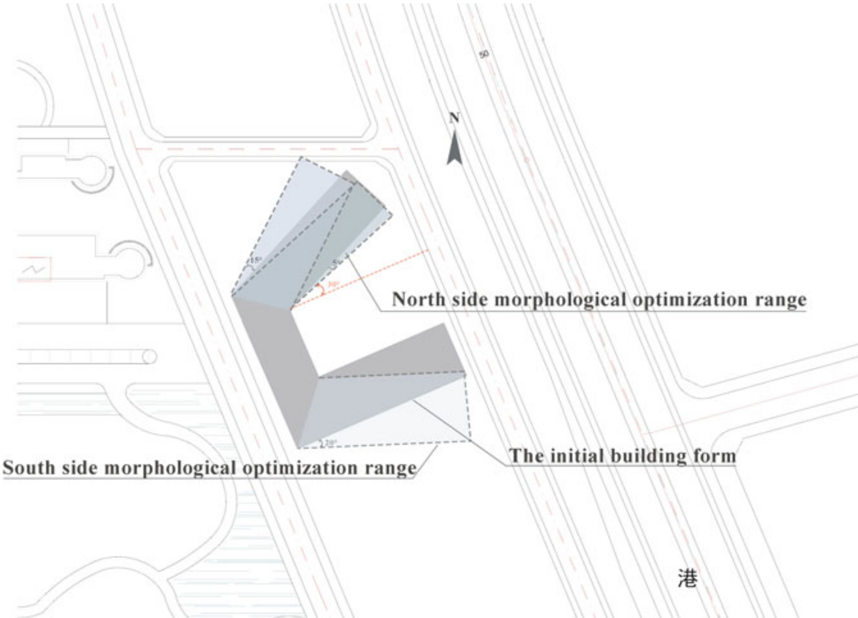


Fig. 11. Angle setting in case of eastward opening

3 Results and Discussion

After 50 generations, the optimization results in each direction tend to be smooth. A total of 2,000 optimization results were calculated, including a total of 205 Pareto front solutions (non-dominated solutions) for the case with the opening facing west and a total

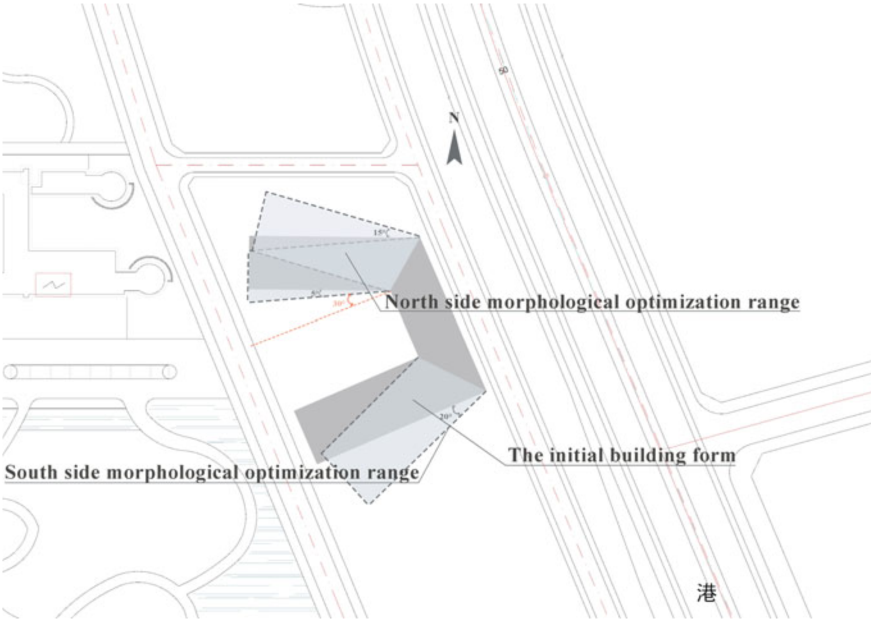


Fig. 12. Angle setting in case of westward opening

Table 3. The value ranges and the steps of variables setting of reference building

Variables	Unit	Value ranges	Steps
Optimized length of the north side	m	57.3–60.0	0.3
Optimized length of the south side	m	71.4–75.0	0.3
Height of each floor of the building	m	3.6–4.5	0.1
North side rotation angle	°	20	1
South side rotation angle	°	20	1

of 301 Pareto front solutions (non-dominated solutions) for the case with the opening facing east (Figs. 17 and 18). The actual running time of the whole process is about 6 h for a laptop computer with an i7-9750H CPU.

3.1 Evolution of Solutions

The gray area shown in the Figs. 19, 20 and 21 is the Pareto front surface of the feasible solution. As the optimization proceeds, the Pareto front surface shrinks continuously and moves closer to the optimization target, and the values of the three targets are significantly reduced in the case of the opening to the east, which means that the solar heat gain value of the building in summer decreases, the inverse of the solar heat gain

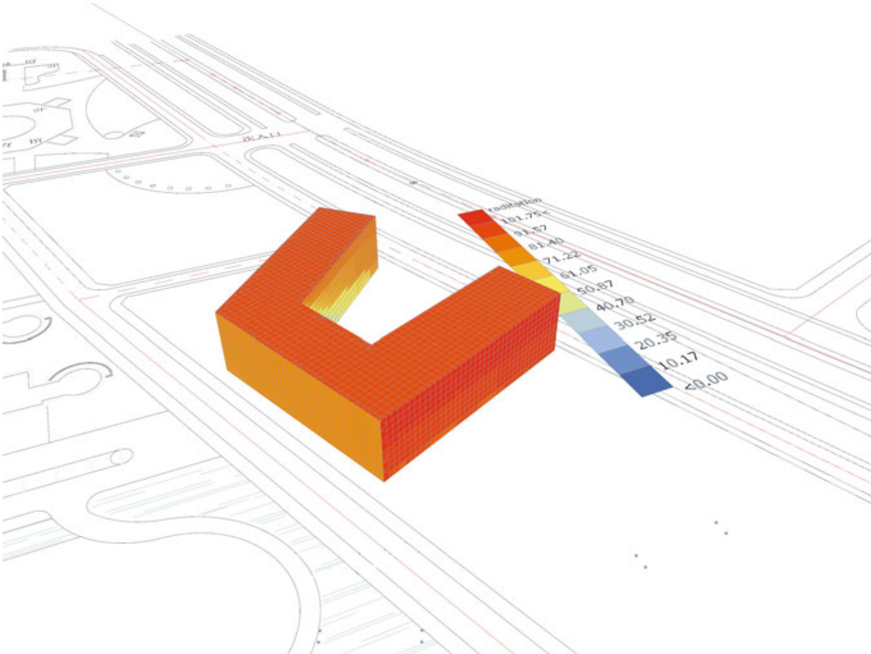


Fig. 13. Simulation of solar radiation heat gain in winter with an eastward opening

value of the building in winter decreases, and the difference between the solar heat gain value in summer and the solar heat gain value in winter decreases, which indicates that the performance of the feasible solution gradually improves.

The values of all three objectives decrease from the optimization to the 35th generation in the case of westward opening (Figs. 22, 23 and 24), which means that the solar heat gain value of the building in summer decreases, the inverse of the solar heat gain value of the building in winter decreases, and the difference between the solar heat gain value in summer and the solar heat gain value in winter decreases, which indicates a gradual improvement in the performance of the feasible solution.

3.2 Selection of the Optimal Solution

After finishing the evolution process of feasible solutions, it is necessary to select the optimal solution. The selection of the optimized solution is based on building performance indexes in the performance value range of more than 50%. The difference between the solar heat gain values in summer and winter represents the combined condition of the two seasons and is the basis for the experiment. By ranking the difference between the two according to the performance metric, the optimal solution can be filtered to ensure that no extreme cases occur. This process can be accomplished by a diamond diagram (Figs. 25 and 26), in which the values of each target are arranged on an axis, with the closer to the origin representing the better value of the target.

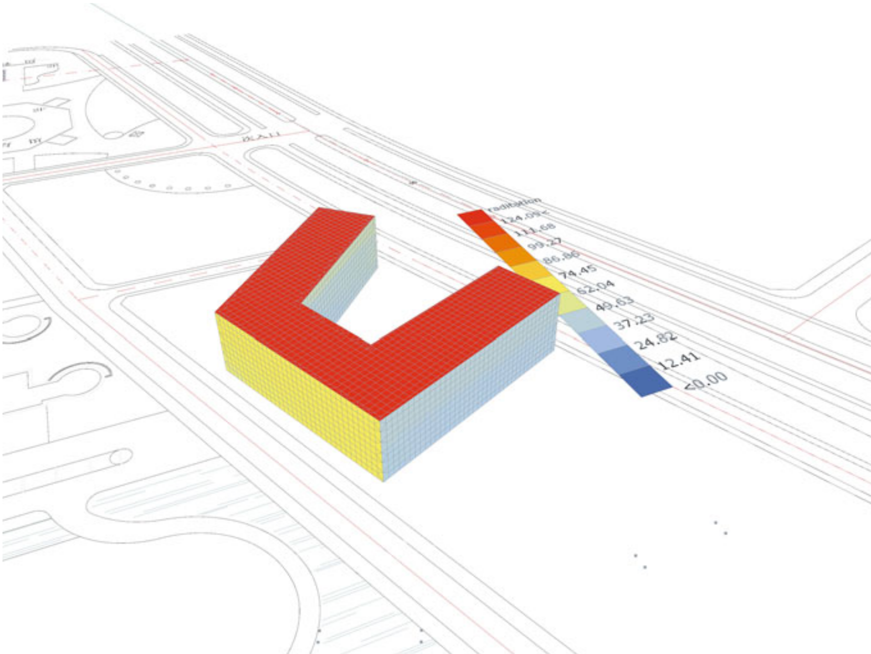


Fig. 14. Simulation of solar radiation heat gain in summer with an eastward opening

After filtering, a critical condition is found where the performance values of each objective are above 50%, beyond which there will be an objective that does not meet the 50% requirement. Within the critical condition, in the case of the east side opening, the length of the north side building should be reduced by 0–2.1 m, which means that the range of length change of the north side should be 57.9–60 m, and the length of the south side building should be reduced by 0–3.6 m, which means that the range of length change of the south side should be 71.4–75 m; the height of the floor should be 3.6–4.6 m; the north side building should not be turned more than 5° to the south and 14° to the north. In other words, the angle with the building opening direction is 25–44°, and the south side of the building should not be turned more than 16° to the south, which means the angle with the building opening direction is 0–16°.

In the case of west side opening, the length of north side building should be reduced by 0–2.7 m, that is to say, the range of length change of north side should be taken as 57.3–60 m, and the length of south side building should be reduced by 0–2.1 m, that is to say, the range of length change of south side should be taken as 72.9–75 m; the floor height should be chosen as 3.6–4.6 m; the north side building should not be turned to more than 5° to the south and 15° to the north, that is to say the angle with the building opening direction is 25–45°, and the south side of the building should not be turned more than 20° to the south, which means the angle with the building opening direction is 0–20°.

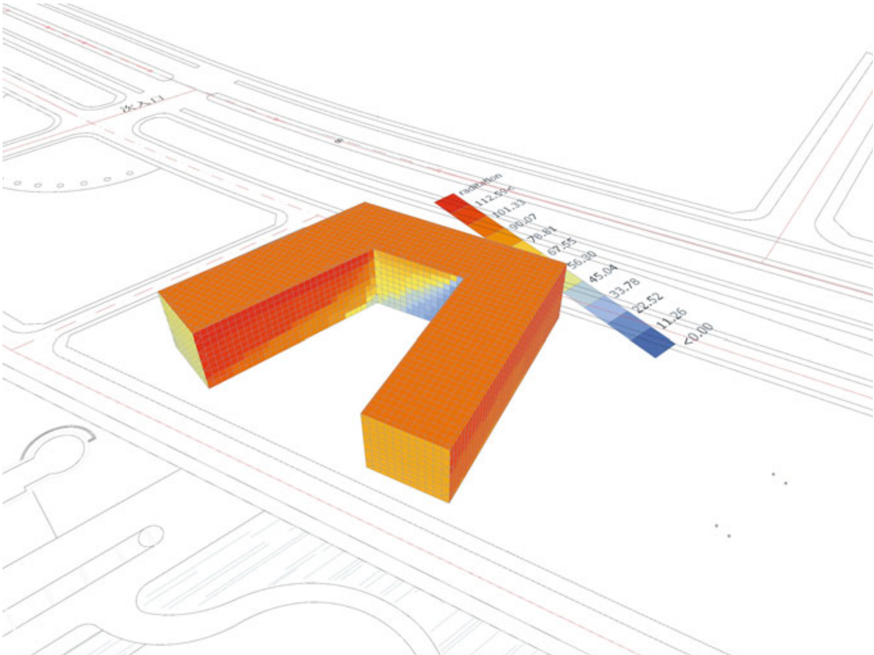


Fig. 15. Simulation of solar radiation heat gain in winter with an westward opening

To sum up, the parameters affecting the performance of the building in the case of the east side opening are the length of the north side building and the angle of rotation of the south side building, and the range of change of the length of the north side should be 57.9–60 m. The angle of the south side building and the direction of the building opening should be 0–16°, the parameters affecting the performance in the case of the west side opening are the length of the south side building, and the range of change of the length of the south side should be 72.9–75 m. As long as these parameters are ensured, the building can obtain high performance in all aspects within the set range.

4 Conclusions

In this study, a multi-objective optimization of U-shaped academic buildings in colleges and universities in cold regions of China was conducted to improve the winter solar heat gain and reduce the summer solar heat gain of the buildings. After 100 iterations, 205 non-dominated solutions were obtained for the westward opening case and 301 non-dominated solutions for the eastward opening case. The article discusses the value distribution of the optimization objectives. The parameter that affects the building performance in the case of east side opening is the length of the north side building and the rotation angle of the south side building, and the range of the variation of the length of the north side is 57.9–60 m, and the angle of the south side building and the direction of the building opening is 0–16°. The parameter that affects the performance in the case of the west side opening is the length of the south side of the building, and it is appropriate

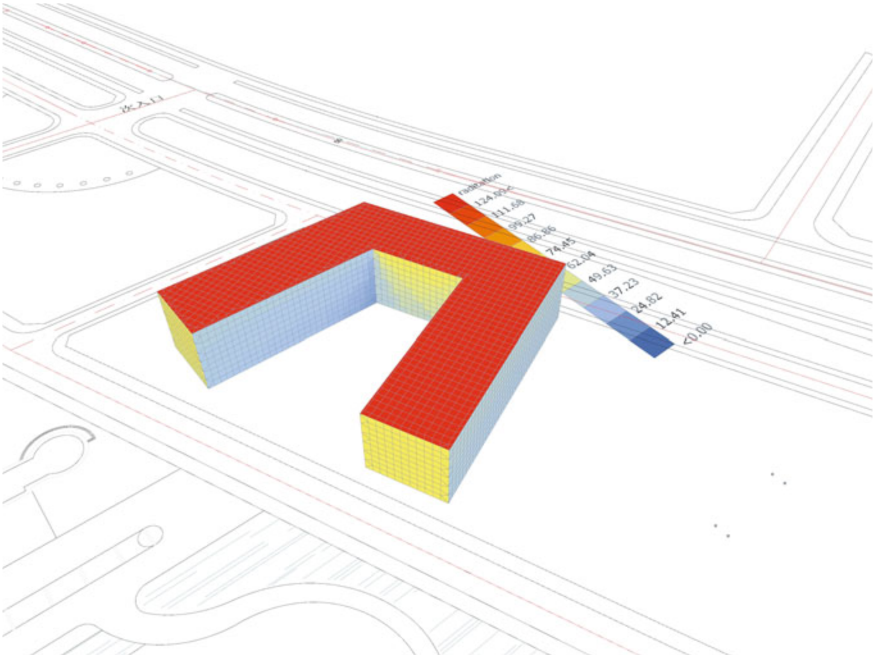


Fig. 16. Simulation of solar radiation heat gain in summer with an westward opening

Table 4. Settings of the optimization algorithm

Algorithm	Size of each population generation	The number of generations of simulated population	Crossover rate
NSGA-II	20	100	0.9

to take the range of 72.9–75 m. The performance of the building is improved through optimization, which proves that in the cold region of China, the reliance of the building on equipment can be reduced and the performance of the building can be improved through the optimization of the building form itself.

In order to improve the optimization efficiency and save the optimization cost, some auxiliary spaces are reduced and simplified, which makes the setting of building form-related parameters not comprehensive enough and difficult to take more factors into account. This is the insufficiency of this study, and the research on this aspect will be discussed in depth in the subsequent related work.

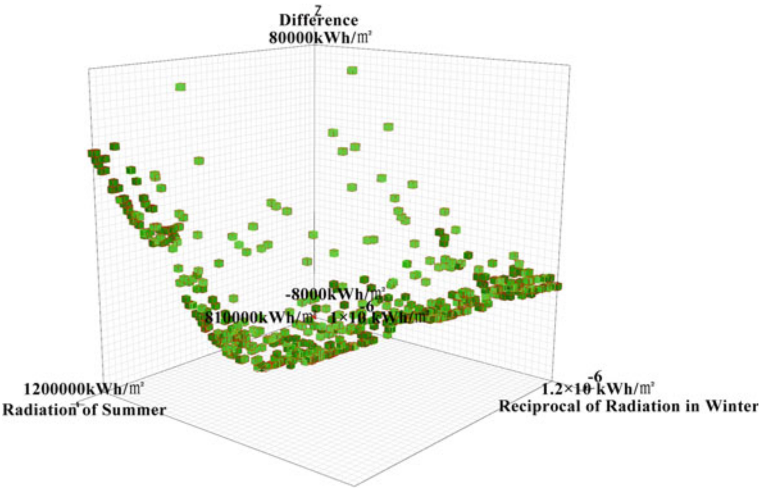


Fig. 17. Pareto front solution in the case of opening to the east

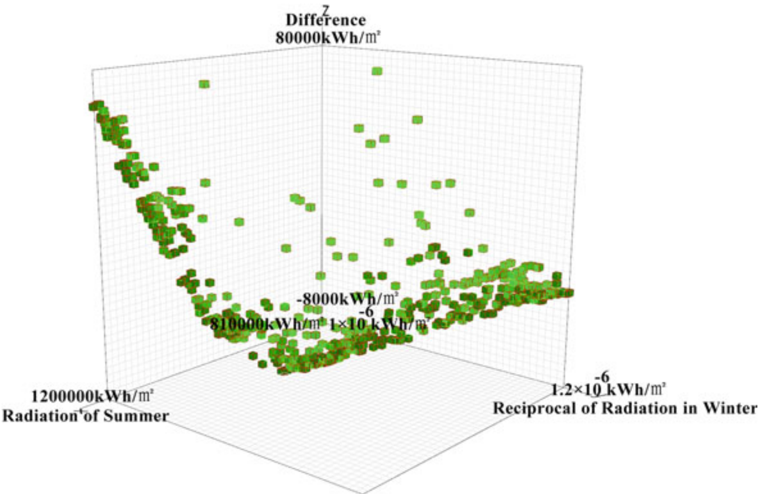


Fig. 18. Pareto front solution in the case of opening to the west

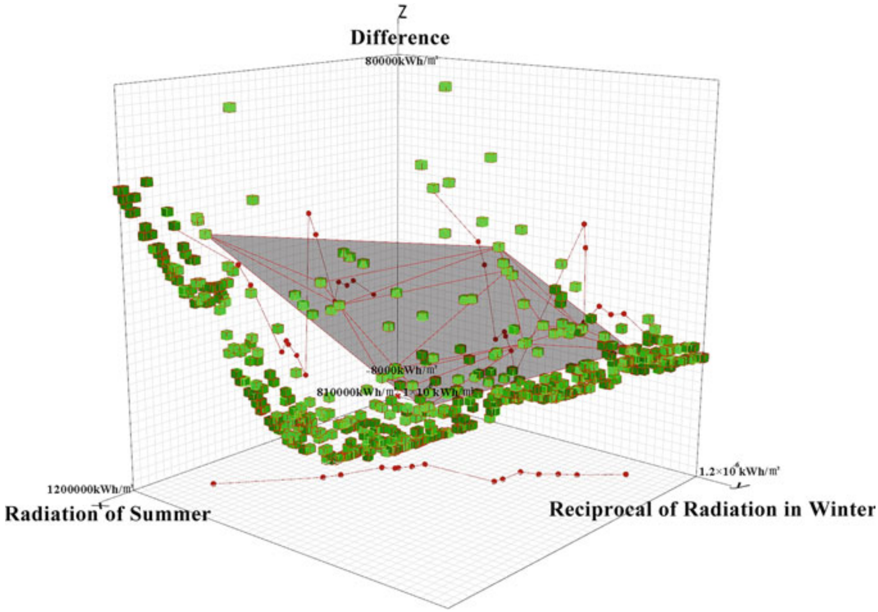


Fig. 19. Pareto front surface at the second generation in the east side case

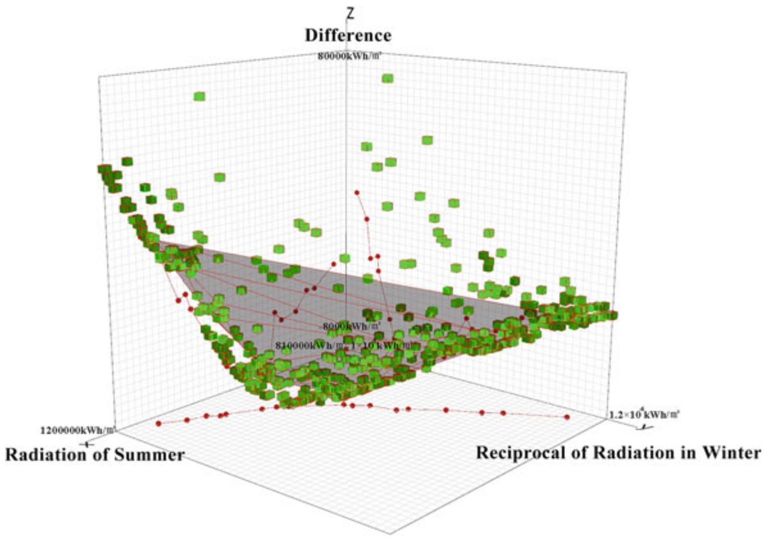


Fig. 20. Pareto front surface at the fifteenth generation in the east side case

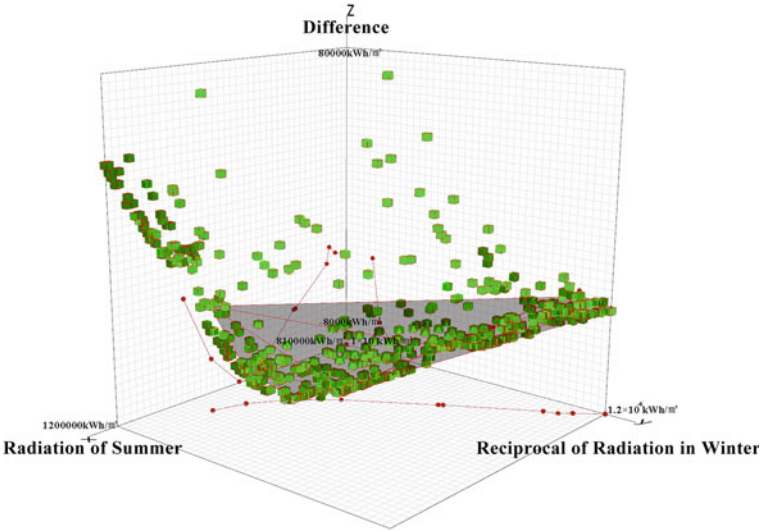


Fig. 21. Pareto front surface at the twenty-seventh generation in the east side case

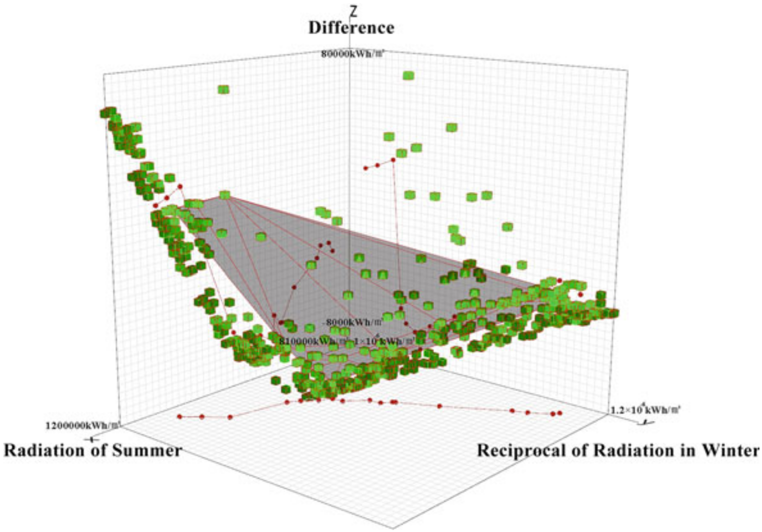


Fig. 22. Pareto front surface at the fifth generation in the west side case

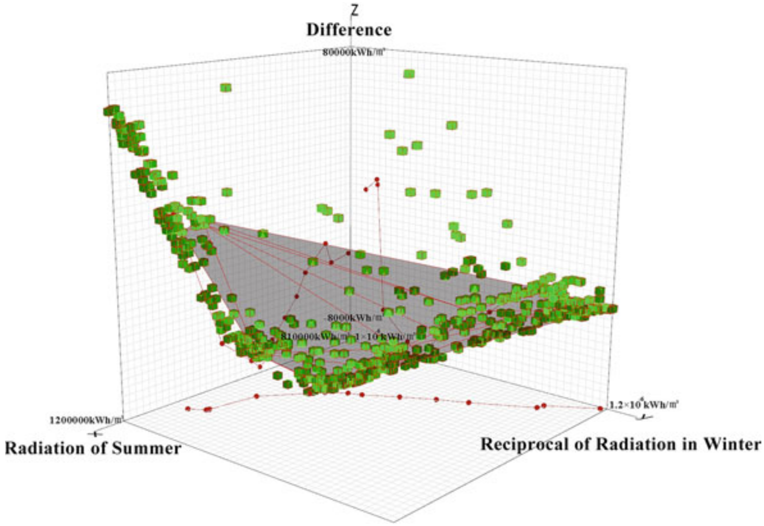


Fig. 23. Pareto front surface at the fourteenth generation in the west side case

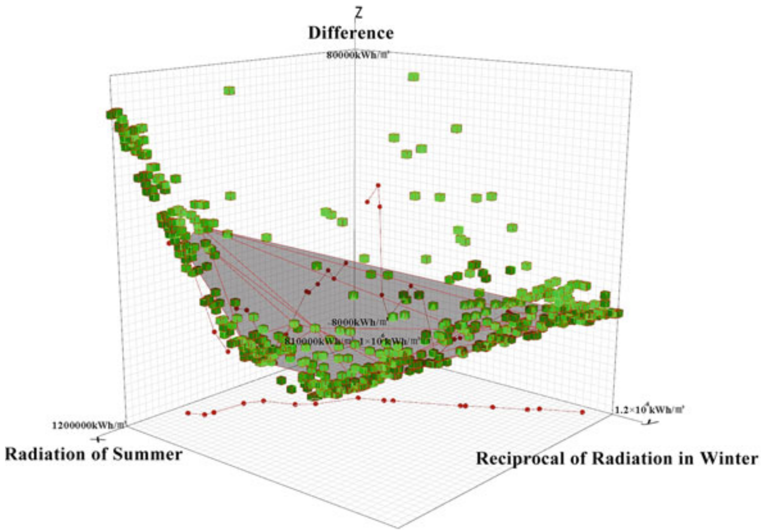


Fig. 24. Pareto front surface at the thirty-fifth generation in the west side case

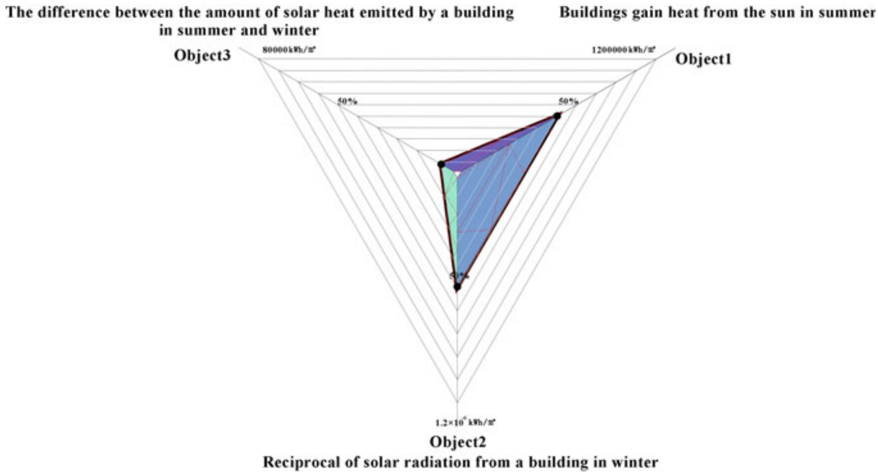


Fig. 25. Diamond diagram under critical conditions with the opening to the east

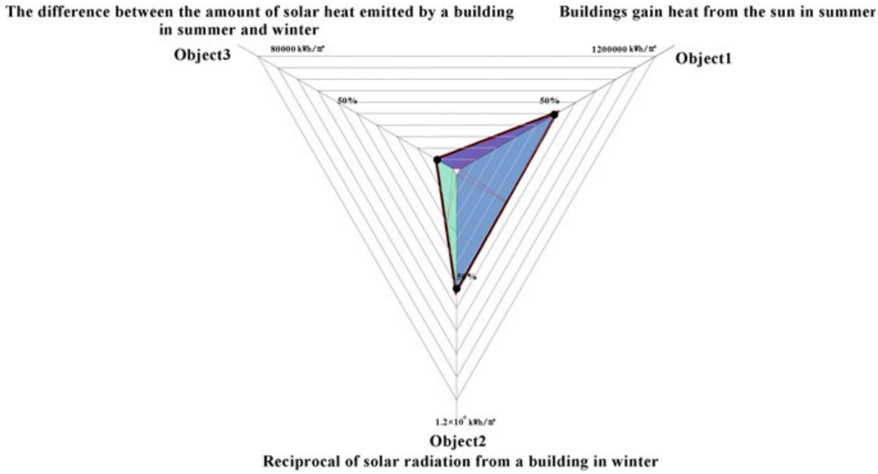


Fig. 26. Diamond diagram under critical conditions with the opening to the west

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