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Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China

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Abstract

In the severe cold zones of China, solar radiation is one of the most important issues in architectural design. The design seeks to make buildings receive more direct sunlight within the limits of the user's comfort and simultaneously save energy and space. So far in China, the design of solar radiation has usually been qualitative, not quantitative, and it is often implemented by architects with experience or those following convention. This rough and rigid design approach is not accurate or efficient, particularly in the design of free-form buildings, which comprise a class of irregular-form buildings popular in current architectural design. Moreover, solar radiation is not the only thing that needs to be considered; shape coefficient and space efficiency should also be considered in free-form building design.

This study proposes a method for a free-form building that receives more solar radiation though shape optimization and takes into account the other two objectives mentioned above.

This paper provides a method with a "Modeling–Simulation–Optimization" framework. In the process of applying this method, parametric modeling with Rhinoceros and Grasshopper is used to build up the free-form building model, and the shape optimization of the building is processed by using the multi-objective genetic algorithm to make sure the three objectives—i.e., to maximize solar radiation gain, to maximize space efficiency, and to minimize the shape coefficient—are all achieved. Finally, a Pareto frontier is generated to show the optimal solutions and to assist designers in making final decisions.

The case study shows that compared with the cube-shaped reference building, the total solar radiation gain of the optimized free-form shape building is 30–53% higher, and the shape coefficient value is reduced by 15–20%, with a decrease of less than 5% of the space-efficiency values.

The proposed method, according to the basic process of architecture design, uses a performance-driven approach to find solutions that satisfy the requirements. It can be used in real architectural design to solve practical optimization problems.

Keywords: Free-form building; Solar radiation gain; Shape optimization; Multi-objective genetic algorithm; Severe cold zone

1. Introduction

Severe cold zones in China are zones where the coldest average temperature for that month is equal to or less than

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10 °C, and the number of days where the average daily temperature is equal to or less than 5 °C is equal or greater than 145 (GB51076-93, 1993; GB51078-93, 1993). Nearly 45% of the total land area of China falls into cold zones, as shown in Fig. 1. As one might expect, energy consumption in building is very high in such regions. For this reason, the Chinese government has implemented a series of standards for regulating architectural designs to reduce the energy consumption of building in severe cold zones. Amongst the many measures of achieving this goal, the most effective and direct approach is to increase the solar radiation gain of the building.

Solar radiation is one of the most important essential factors of building design. Most researchers consider that sunlight plays a positive role in improving comfort, health, and energy performance (Ne'eman et al., 1976; Ne'eman, 1977; Boyce et al., 2003), particularly in severe cold zones. However, in China, the solar design of buildings is often created according to the designer's experience, by the simple formula calculation and only for purposes of meeting design codes. This rough and rigid design approach is not accurate or efficient, and although it can be applied to simple-form buildings, it is not suitable for complex free-form buildings.

Free-form buildings are those with free-curved surfaces that have no geometric representation (Vizotto, 2010). It is difficult to use only simple formulas to calculate solar radiation accurately. Computer simulation is a good way to solve this problem. Jin and Jeong (2013, 2014) discussed the solar heat gain and energy performance issues of free-form buildings and used a computer to simulate and optimize the free-form building shape.

Solar radiation is not the only issue of building design; the shape coefficient is also an important factor in Chinese building codes. The shape coefficient is the ratio of the area of a building's external surface (F_0) to its inner volume (V_0). It is not only an indicator to measure the complexity of architectural form but also a key factor to evaluate buildings' energy performance. There are many criteria of the shape coefficient for various building types in severe cold zones of China. For example, the shape coefficient for public buildings of more than eight hundred square metres must be less than 0.4. The shape coefficient in severe cold zones requires strong control—in simple words, the smaller the better (GB50352-2005, 2005; GB50189-2015, 2015).

In actual building design, solar radiation and the shape coefficient tend to interact with each other. When a building expands the solar radiation area to increase the solar radiation gain, the shape coefficient will often subsequently increase. It becomes necessary to use an optimization method coupled with energy simulations to find the optimal building shape that balances the two objectives.

2. Literature review

This section provides a brief literature review of studies on the simulation-based optimization of solar radiation, the shape coefficient and building shape.

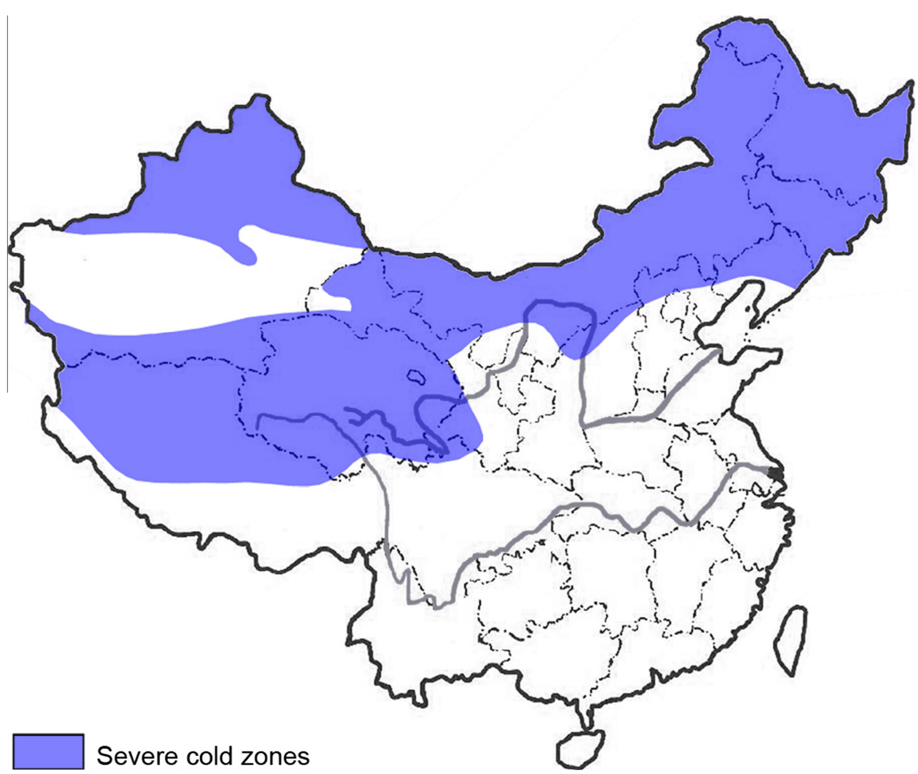


Fig. 1. Severe cold zones in China.

Kämpf and Robinson (2010) provide a method for optimizing building and urban geometric forms for the utilization of solar irradiation using a hybrid co-variance matrix adaptation evolution strategy and a hybrid differential evolution algorithm. Solar irradiation is predicted using RADIANCE (http://radsite.lbl.gov/radiance/) in conjunction with a cumulative sky model. Three different cases are investigated: a group of cuboid-shaped buildings within an urban grid; a small group of geometrically more complex buildings adjacent to a large existing building; and a building with a rectangular plan whose volume has been parameterized as a Fourier series. These cases suggest that the method consistently converges toward an optimal solution. Based on an initial subjectively chosen form, the solar energy available for utilization may be increased by up to 20%. Furthermore, it sometimes yields highly non-intuitive but architecturally interesting forms.

Kämpf et al. (2010) combined a multi-objective evolutionary algorithm with RADIANCE to maximize the heating season solar irradiation offset by envelope heat losses. They provided a case study of the centre of the Matthäus district in Basel, Switzerland and parameterized three urban forms: the Terraces Flat Roofs, the Slabs Sloped Roofs and the Terrace Courts. The parameters are the height of buildings up to their facade and the height and orientation of roofs, with the constraint of maintaining an overall built volume. The method not only is able to examine the relative efficiency of existing urban settlements but also can design new urban forms.

Yi and Kim (2015) propose a method that uses an agent-based geometry control system that introduces fewer control points to reduce the cost and time of computation. A genetic algorithm is used to optimize the building's access to direct sunlight by changing the variables: the location and rotation of the building, the twist factor and the scale factor. The paper selects a "Y"-shaped building for the test and the results indicate that the method can ensure optimal performance without restricting design possibilities.

Ouarghi and Krarti (2006) combine a neural network and genetic algorithm to optimize the selection of building shape. The footprint dimensions of the building are optimized to minimize the energy and construction costs, and its volume and height are predefined. The design parameters include climate, window-to-wall ratio, type of glazing, and wall or roof insulation, and the models are created for four locations: Cairo, Gabes, Rome and Tunis. The neural networks are first used to create an approximate model for predicting the energy use; then, the genetic algorithm is used in the optimization process to reduce the computation time.

Wang et al. (2006) present a methodology to optimize the building shape with the objective functions of lifecycle cost and lifecycle environmental effects using a genetic algorithm. The building footprint is represented by a multi-sided polygon. In addition to the shape description, the design variables include structural systems, insulation levels, glazing type, windows-to-wall ratio and overhangs. Pareto solutions have been found for a case study of an office building located in Montréal, Canada. The results show that the lower lifecycle cost solutions have shapes close to a regular polygon, and the lower lifecycle environmental effects solutions have a larger edge length on the south facade.

Tuhus-Dubrow and Krarti (2010b) developed a simulation-optimization tool that couples a genetic algorithm to a DOE-2 engine to minimize the energy use and lifecycle cost for residential buildings. The design variables include the building shapes—e.g., rectangle, L, T, cross, U, H, and trapezoid—wall and roof constructions, foundation types, insulation levels, and window areas and types. The results indicate that when only shape variables are varied, the trapezoid shape shows slight benefits compared to other shapes due to the effects of solar radiation through the windows. However, when all the design variables are allowed to vary, the square shape provides the lowest life-cycle costs in all climates.

Jin and Jeong (2013, 2014) suggest a simple way of determining thermal characteristic and propose an optimization process for a free-form building shape based on it. The geometric modeling of a model free-form building is performed, and the building's surface is divided into finite elements by generating a mesh. A genetic algorithm is applied to the optimized shape of the free-form building for various climate zones. The results indicate that the process can rapidly predict and optimize the variation of the solar and envelop heat characteristics caused by varying the building shape.

Depecker et al. (2001) relate heat consumption to the shape coefficient of buildings. Fourteen buildings conceived from cubes with sides 5.4 m high are placed in two climates: the cold climate of Paris and the mild Mediterranean climate of Carpentras in southern France. Their heating consumption is estimated using the calculation code. The results show that the energy consumption of buildings is proportional to the shape coefficient in cases of cold, severe and scarcely sunny winters.

Oral and Yilmaz (2002, 2003) introduce a methodology for determining the maximal feasible heat-transfer coefficient (U value) of a building that ensures thermal comfort while minimizing energy conservation. The limit U value depends on the building's form, represented as the shape coefficient, glazing type, windows-to-wall ratio and wall orientation. The methodology is applied to three Turkish cities, Istanbul, Ankara, and Erzurum, which are representative cities of Turkey's temperate humid, temperate dry and cold zones. The result shows that the methodology can be used in temperate and cold zones with long and intensive heating periods.

From the literature review, we find the following: (1) The approach that combines optimization algorithms and simulation tools has become a common method to address the problem of solar radiation and building-shape optimization in recent years. (2) Genetic algorithms are successful at finding high-performance design solutions, and they have been used more than other algorithms. (3) Most studies focus on regularly shaped buildings, and the research on free-form building-shape optimization is just beginning. (4) Research that combines the shape coefficient and solar radiation in severe cold zones is insufficient. (5) Research that includes the usage of building space as an optimization objective is inadequate.

3. Methodology

Conventional optimization of building shapes focused primarily on simulating building performance; the usage of building spaces, one of the most important issues in architectural design, is rarely addressed. This problem is particularly prominent in the process of addressing free-form building. There must be a quantitative indicator of the usage of building space. In architectural design, there is often a considerable amount of space that is difficult to use, which leads to unnecessary energy and material consumption. Then, it is necessary to minimize these spaces when optimization is in process. The paper proposes using a parameter of space efficiency to represent and quantify the effective usage of building space. Then, space efficiency is equal to the usable space volume divided by the total volume of the building.

$$E = V_u / V_0 \tag{1}$$

where E is the space efficiency, V_u is the useful space volume, and V_0 is the total inner volume of the building. Meanwhile, the space efficiency of multi-story buildings can be stated as:

$$E = \frac{\sum_{i=1}^{n} (V_u)_i}{V_0} \tag{2}$$

where n is the building's total stories, and i is the number of stories.

For regular-form buildings, there are simple formulas to describe the shape, and the volumes can be easily calculated. However, in free-form buildings, it is difficult to describe the shapes of buildings, and the calculation is much more difficult. Therefore, a computer-aided method with a “Modeling–Simulation–Optimization” framework is proposed to make the calculation much easier. Additionally, it can help simulate and compute the other two optimization objectives: solar radiation and shape coefficient.

In this paper, the shape-optimization objectives are maximum solar radiation gain and space efficiency and a minimum shape coefficient. The overall process is shown in Fig. 2. It contains three parts: geometric modeling, simulation and GA optimization. A dynamic model is established using the NURBS geometry tools in the parametric modeling process. The model can accurately describe the shape of free-form buildings and can be modified swiftly. The performance of the design is calculated using the simulation tool to show the design and to make the data visible. Finally, GA is used to create a new generation of the design and to determine whether it meets the optimization objectives; if not, a new generation will be created until the objectives are met. The steps are as follows: (1) environmental analysis, (2) determination of variables and constraints, (3) parametric modeling, (4) simulation and calculation, (5) application of MOGA, and (6) evaluation of results using Pareto frontier.

3.1. Environmental analysis

Environmental analysis is a prerequisite for the optimization of building shape. The analysis is divided into two parts. The first part includes the natural conditions, such as climate, temperature, precipitation, sunshine and other conditions in the area that can be obtained from the EnergyPlus Weather file (.epw) (https://energyplus.net/weather). The second contains the urban environmental conditions, particularly the heights, sizes and layouts of the buildings around the base, which may have great effects on the solar radiation gain of the building. These environmental constraints need to be extracted and analysed before optimization, which will affect the optimization process by transforming the elements into optimization constraints to affect the architectural form.

3.2. Determining variables and constraints

There are three types of variables that describe a building shape: the static parameters, the dynamic parameters and the dependent parameters. The static parameter is a fixed value that stays the same in the optimization process. The dependent variable is determined by the constant and independent variables. Therefore, the independent variables play decisive roles in the optimization process. The independent variables are what the designer can input and modify to generate the design; examples include the orientation, the size of floors, the floor heights, and the number of stories. These variables are used to generate the parametric model and input into the simulation and calculation programmes to obtain the results. For the shape of free-form buildings, the most basic independent variables are the control-point coordinates of the curve and the surface, and each control point coordinate is made up of three variables (X, Y and Z coordinates).

Constraints define the conditions that need to be satisfied by variables. For the control-point coordinates, the constraint can be expressed as a range of three-dimensional space. These constraints may come from the environment, building function or important government codes and standards. The step is the minimum unit of variable changes that also need to be well defined. Overly large steps will cause a lack of accuracy, but overly small steps may lead to excessive time consumption.

Moreover, the location of the original point should be highlighted. It is located not only at the centre of the shape but also outside the building. Regardless of where it is located, it is needed to make the variables and constraints simpler and clearer.

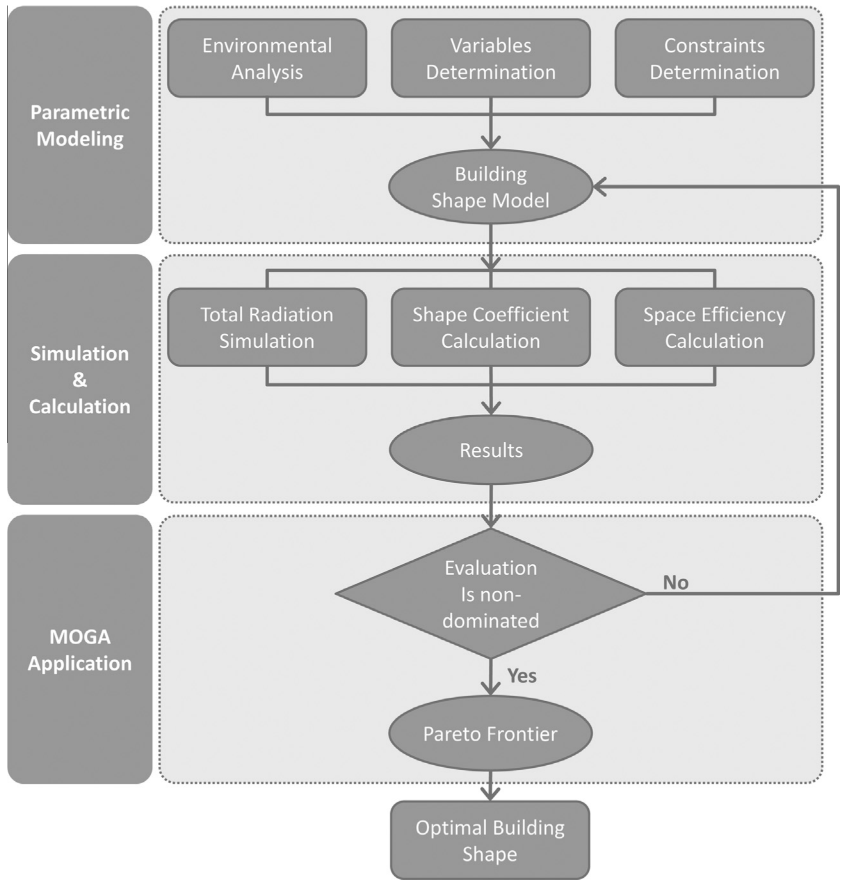


Fig. 2. Overall work frame.

3.3. Parametric modeling

For free-form building optimization, it is necessary to generate and demonstrate the building shape accurately and quickly and to adjust and modify the shape frequently. Therefore, we must create a popular parametric modeling method that is a combination of Non-Uniform Rational B-Splines (Nurbs) modeling and a parametric design. Based three-dimensional design programme called Rhinoceros, by Robert McNeel & Associates (http://www.rhino3d.com/). Nurbs is used to demonstrate the shape of free-form buildings. Grasshopper (http://www.grasshopper3d.com/), a parametric design add-in programme of Rhinoceros, is used to combine the design information and conditions together, to integrate the variables and constraints, and to generate the parametric model dynamically. This method allows the designer to programme the building shape and to modify it by changing the input variables without having knowledge about the scripting. Parametric modeling can also provide a quantified building shape that can be used by simulation and calculation.

3.4. Simulation and calculation

3.4.1. Solar-radiating simulation

To achieve the accuracy and efficiency of solar-radiating simulation, this paper uses Ladybug (http://www.grasshopper3d.com/group/ladybug), an open-source environmental plug-in for Grasshopper, to calculate the amount of solar radiation gain. Ladybug uses a Climate-Based Daylight Modeling (CBDM) method to simulate the daylight radiation based on the meteorological data extracted from an EnergyPlus Weather file (.epw) for a specific location. The solar radiation function in Ladybug uses the Cumulative Sky approach (Robinson and Stone, 2004) to calculate the amount of radiation of the Tregenza Skydome. The total solar radiation falling on the test model and the amount at each test point on the surfaces are accumulated. The calculation results have been tested and shown to be reasonable (Roudsari and Pak, 2013). Yi and Kim (2015) combined Ladybug with an agent-based hierarchical geometry method to optimize solar hours and building layouts quickly and efficiently.

3.4.2. Space-efficiency calculation

The space occupied by human activities is the main basis on which to determine the interior space scale of the building. A space with clear height of 2.1 m or lower may restrict the activities of Chinese people. Assuming the structure thickness is 100 mm, the structure's story height will be 2.2 m. Stories higher than 2.2 m are calculated as useful space, and story heights shorter than 2.2 m high are excluded. For example, the building in Fig. 3 is a section of a free-form building, and it has three stories with a

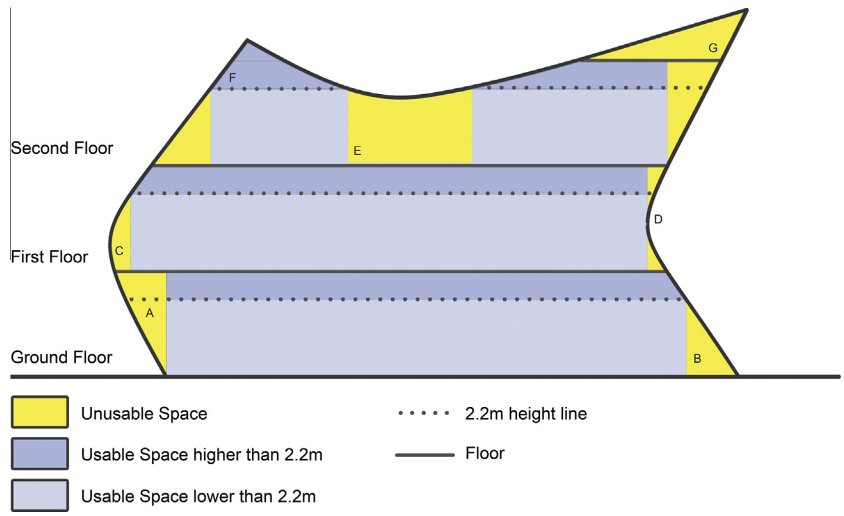


Fig. 3. Example for space coefficient calculation.

height of 3 m. Because of its special shape, there are several unusable spaces, marked in yellow[1], which show several cases of unusable space calculations. Zone A is a space with a roof area larger than the floor area, so the edge of the floor is the boundary of usable space. Zone B is a space with a larger floor area than roof area, so the space lower than 2.2 m does not need to be calculated. Zone C is similar to zone B; despite the inwardly curved wall, the roof area is still smaller than the floor area, so the space lower than 2.2 m does not need to be calculated. Zone D has a concave wall, so the spaces between the lowest points of the depression are both unusable. Zone E has a concave roof; the space lower than 2.2 m cannot be used well, so it cannot be calculated. Zones F and G are both roof spaces, but zone G is divided by a roof. Therefore, these spaces cannot be included. The unusable spaces of a free-form building are often so fragmented and scattered that it is difficult to produce statistics on them. Therefore, it is necessary to use a computer to simulate, analyse and calculate such spaces.

3.4.3. Shape-coefficient calculation

The formula of the shape coefficient is as follows:

$$S = F_0/V_0 \tag{3}$$

where F_0 is the building's external surface area, and V_0 is its inner volume. These two values can be easily computed in the parametric model, so this process is not treated in detail.

3.5. Application of MOGA

Many algorithms can be applied to optimize the performance and shape of buildings. Geroa et al. (1983) created a model and used brute-force search to optimize the thermal performance, capital cost and usable area by modifying the building shape and glazing properties. Kämpf and Robinson (2009, 2010) used a hybrid CMA-ES/HDE algorithm to vary the placement of buildings to optimize solar irradiation availability. Wang et al. (2006) optimized the floor shape of a green building base on the LCEI and the LCC with MOGA. Tuhus-Dubrow and Karati's (2010a) research showed that when there are 10 or more variables, the genetic algorithm is more efficient and accurate. The genetic algorithm is often used in simulation-based optimization problems because it presents several advantages: GA does not require the objective function to be continuous; it is a global search technique that can escape from local optima more easily, and it can find multiple Pareto solutions for a multi-objective optimization problem in one run (Wang et al., 2005). Therefore, in this paper, a multi-objective genetic algorithm is applied to obtain the trade-offs among solar radiation, shape coefficient and space efficiency.

In this paper, a plug-in for Grasshopper, called Octopus, a real number representation optimization tool, is applied to perform the optimization (http://www.food4rhino.com/project/octopus). Octopus applies evolutionary principles to parametric design and solution finding, allows for a multi-objectives optimization process, and allows for the production of a set of trade-off solutions among each objective. Importantly, Octopus still allows the whole optimization process to be visual and controllable.

3.6. Evaluating results using Pareto frontier

After the above optimization process is executed, the simulation and calculation results are generated. There are two common methods to evaluate the results of multi-objective optimization. The first is called the weighted-sum approach, and it assigns weights to different optimization objectives so that it can combine the various

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

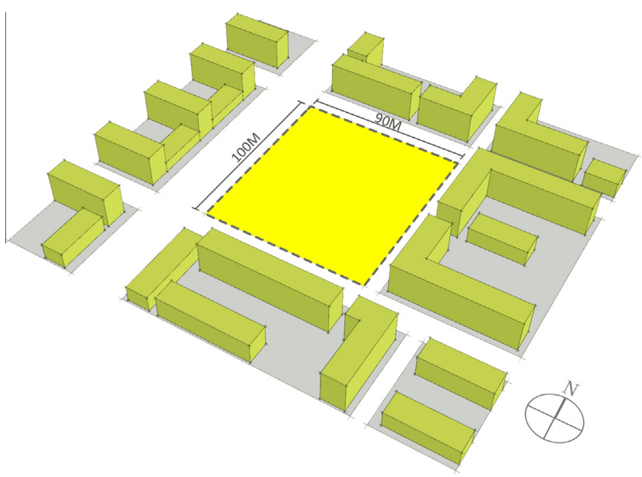


Fig. 4. Case site and surrounding buildings.

objectives to form a single objective and treat it as a simple optimization problem. For this study, giving a reasonable weight to each target is difficult, and cannot be done accurately enough; therefore, this approach is not suitable.

The other is a true multi-objective optimization method called Pareto optimization. It aims to achieve a balance between different objectives and to find non-dominated solutions. A non-dominated solution is also called the Pareto optimal solution, and it is not dominated by any other solution in the solution space. All non-dominated solutions form a set called the Pareto frontier.

4. Case study

4.1. Overview

The case study takes the shape-optimizing process of a community centre building in Shenyang as an example. Fig. 4 shows the base and surrounding conditions of the building. The site is rectangular with a size of 90 m×100 m. Residential buildings surround the base, with heights lower than 18 m due to planning restrictions.

The core space of this building is a 30 m×20 m×14 m hall designed to host sports and cultural activities. This is the most important restraint for the optimization. Many other subordinate spaces, such as those for transportation,

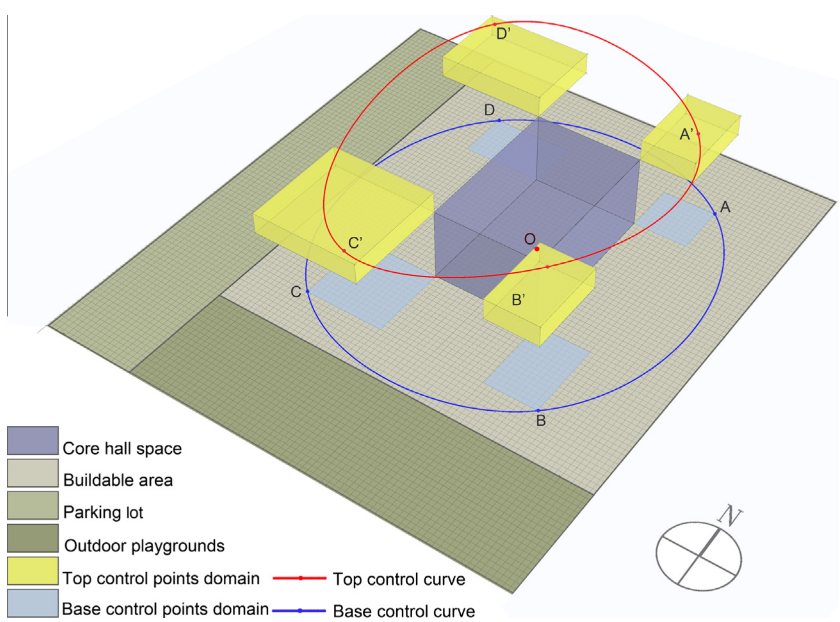


Fig. 5. Buildable area and variables domain.

Table 1
Domains of the control points.

Control points	X_{min}	X_{max}	X_{domain}	Y_{min}	Y_{max}	Y_{domain}	Z_{min}	Z_{max}	Z_{domain}
A	10.0	20.0	10.0	15.0	25.0	10.0	0	0	0
B	10.0	20.0	10.0	−15.0	−25.0	15.0	0	0	0
C	−10.0	−25.0	15.0	−15.0	−30.0	15.0	0	0	0
D	−10.0	−25.0	15.0	15.0	25.0	10.0	0	0	0
A'	10.0	20.0	10.0	15.0	30.0	15.0	14.0	18.0	4.0
B'	10.0	20.0	10.0	−15.0	−30.0	15.0	14.0	18.0	4.0
C'	−10.0	−30.0	20.0	−15.0	−35.0	20.0	14.0	18.0	4.0
D'	−10.0	−30.0	20.0	15.0	30.0	15.0	14.0	18.0	4.0

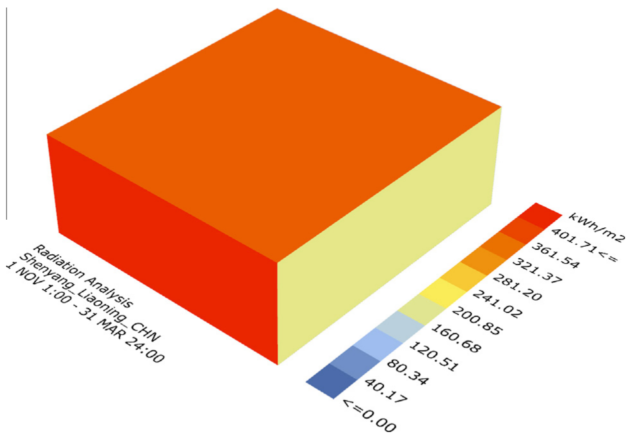


Fig. 6. Solar radiation gain of reference building.

rest, and flow distribution, will be arranged around the core hall.

4.2. Variables and constraints

According to the functional requirements, there should be a parking lot and spaces for outdoor activity around the building. Based on the environmental analysis, the area on the west side should be used as a traffic and parking lot because it faces the main road. The area on the south side of the building should be the outdoor playground to keep the building out of the shade of the southern buildings. The buildable area is shown in Fig. 5. All of the above information became the constraints to the shape variables, and all are from the environment analysis.

The building shape is generated from two major curves. The base curve controls the plan of the building, and the top curve makes up the shape of the freeform. Both of the curves are generated from the four points located in different zones around the main functional hall space. In Rhinoceros, the degree of the curves is set to 3, the weights are set to 1, and the parameterization is set to "chord" to obtain a unique curve. The vertexes of the rectangle spaces are the limitations of the region in which the control points must be located. Otherwise, the curve they generate may go through the core function area. The base centre of the hall is set to the origin of the coordinates, which is convenient for the accurate expression.

There needs to be a larger area near the entrance in the west side of the building as a vestibule to organize traffic. The area on the south side can get more sunshine, so this area should also be expanded accordingly. The domains of the top control points are similar, but to ensure more

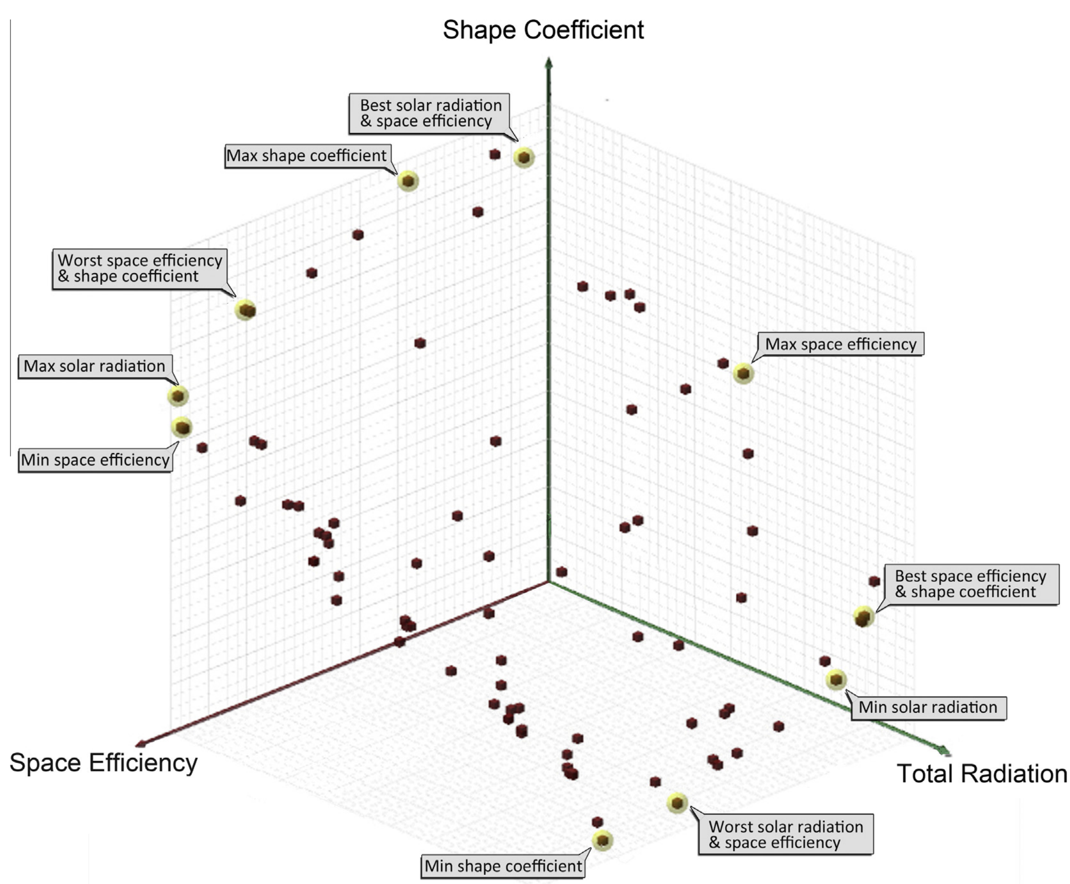


Fig. 7. Pareto frontier of the optimization.

solar radiation and the possibility of the shape variation, they are enlarged in moderation. Because the limitation of the building height is 18 m, the upper bound of the Z coordinates is set to 18. To ensure the accuracy and efficiency of the optimization, the steps of the variables are set to 0.1. The range of coordinates of points changing in the X, Y, and Z axes is represented by the X domain, the Y domain and the Z domain. The variables and domains are shown in Table 1.

Shenyang's heating period is from November 1 to March 31 of the following year; therefore, the solar radiation simulation period is the same.

Therefore, the number of building shape control variables is 20, and changes in each variable will cause the building shape to undergo an appropriate transformation. In other words, when the building volume increases, the shape coefficient will decrease consequently; this will cause the base control points to approach the maximum value and became constant. Subsequent experiments will show this situation.

4.3. Reference building

To verify the optimizing results, a reference building is defined. The reference building is cube shaped and 50 m×45 m×18 m in size. The size is set to be the maximum value of the domain to make sure that the total solar radiation gain and space efficiency can achieve maximum value. The reference building also needs to be simulated and calculated independently to obtain reasonable reference results, as shown in Fig. 6.

4.4. Genetic algorithm settings

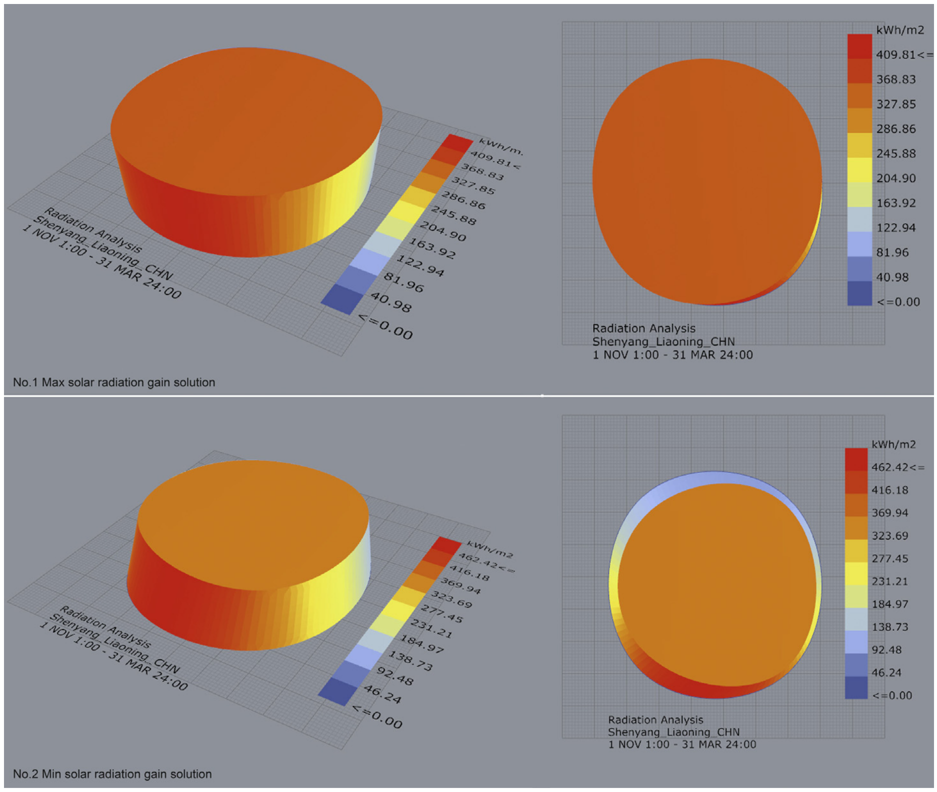
For this case, the following GA parameters' values are set: the population size = 50, maximum generations = 100, crossover rate = 0.8, mutation probability = 0.1, mutation rate = 0.5 and elitism = 0.5. The optimization is performed on a computer with Windows 7 system (4 core 3.1 GHz processor, 8G RAM), and the calculation takes 8.2 hours. The results are presented next.

4.5. Optimization results

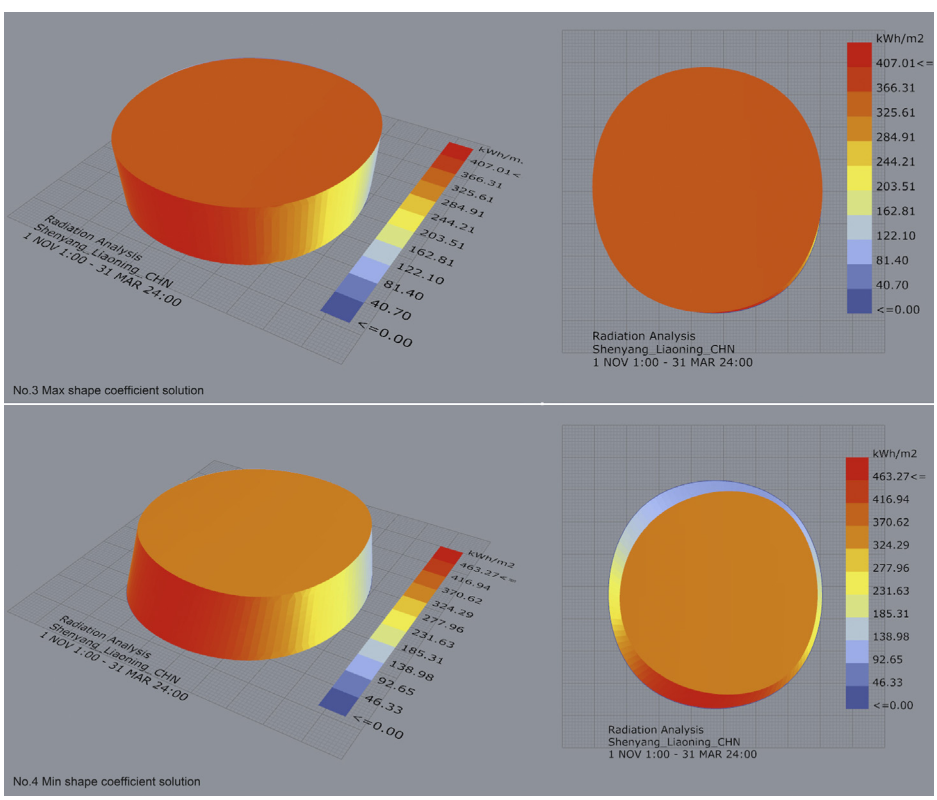
After the operation of 100 generations, 84 non-dominated solutions are generated. They form a Pareto frontier and are expressed by a curved surface. As Fig. 7 shows, all these solutions are non-dominated in the solution space and can be chosen as the final design solutions, but each solution has its own emphases. The solutions with the best and worst performance in the three optimization objectives are compared. The solutions with the maximum and minimum products of each pair of optimizing objective values are also chosen as characteristic solutions to make comparisons because the maximum and minimum products of pairs of optimizing objectives mark the best or worst synthetic performances of the

Table 2
Summary of the 10 characteristic solutions.

No.	Solar radiation (kW h)	Shape coefficient	Space efficiency (%)	Top control points coordinate values (control point–axis)											
				A′–X	A′–Y	A′–Z	B′–X	B′–Y	B′–Z	C′–X	C′–Y	C′–Z	D′–X	D′–Y	D′–Z
1	2245062.58	0.1169	95.12	19.3	29.7	17.2	19.0	−28.6	18	−27.6	−30.2	18.0	−29.8	29.9	18.0
2	1911205.18	0.1134	97.97	18.4	23.0	17.2	18.5	−29.0	17.5	−28.1	−18.9	17.6	−24.3	18.9	17.6
3	2220862.79	0.1189	97.08	19.2	29.7	17.2	19.1	−29.1	17.3	−28.1	−29.5	17.6	−29.7	30.0	17.2
4	1934227.08	0.1121	95.93	18.5	24.2	17.3	19.1	−27.9	18.0	−27.0	−20.5	18.0	−22.8	19.7	18.0
5	2066960.23	0.1163	98.76	17.9	29.3	17.3	19.1	−29.2	17.4	−27.5	−27.1	17.5	−22.3	27.9	17.2
6	2235426.34	0.1165	95.05	19.4	29.7	17.3	19.2	−28.2	18	−28.9	−26.9	18.0	−29.8	29.9	18.0
7	2213196.92	0.1187	98.16	19.8	29.6	17.2	19.0	−29.3	17.4	−27.4	−28.0	17.1	−29.8	29.8	17.5
8	1921279.93	0.1124	96.51	18.5	22.5	17.2	18.5	−28.5	17.9	−28.4	19.0	18.0	−24.3	19.4	18.0
9	1929618.02	0.1138	98.43	19.2	24.2	17.2	18.6	−28.6	17.4	−27.7	−20.7	17.6	−24.5	18.7	17.4
10	2242770.91	0.1177	95.73	19.7	29.7	17.3	19.2	−28.2	17.4	−28.9	−29.5	18.0	−29.8	29.6	18.0

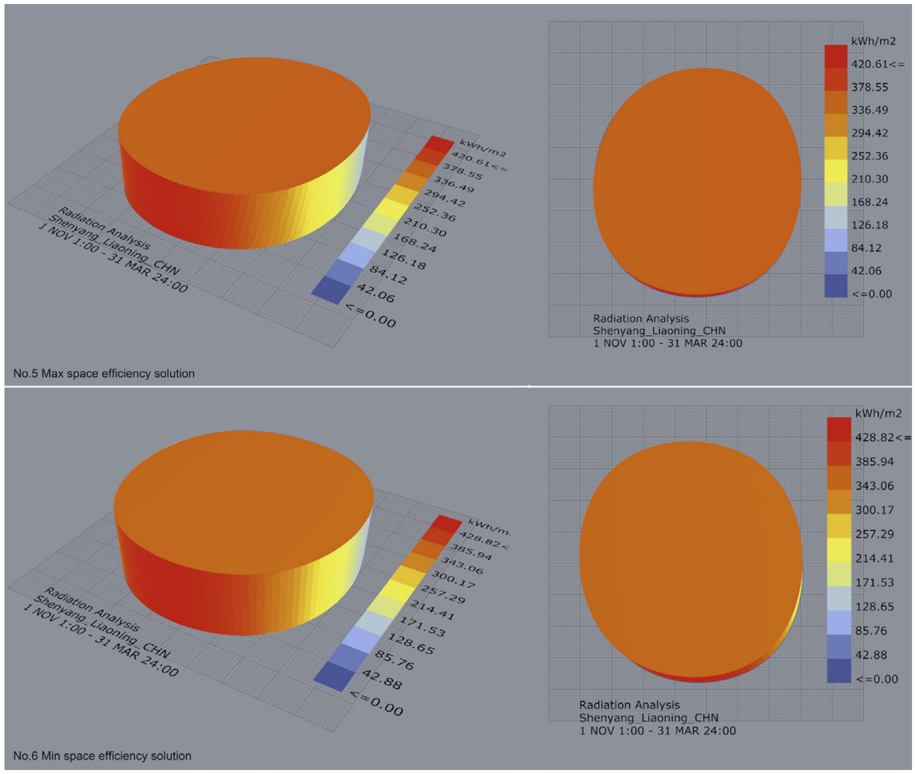


(A) Max solar radiation gain solution vs. min solar radiation gain solution

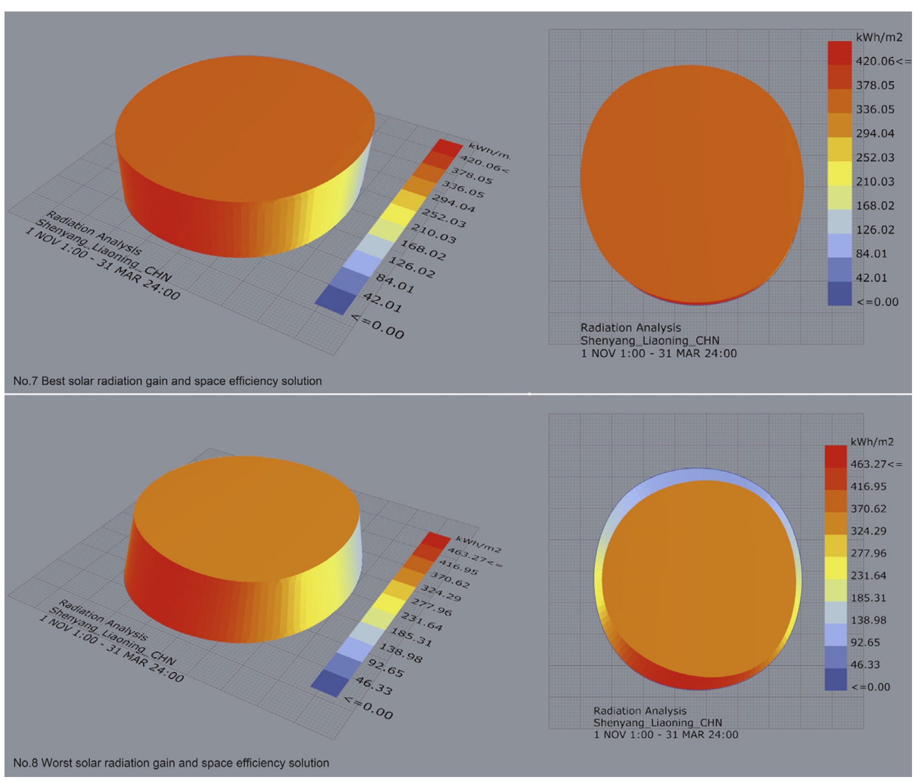


(B) Max shape coefficient solution vs. minshape coefficient solution

Fig. 8. Building shape comparison of characteristic solutions.

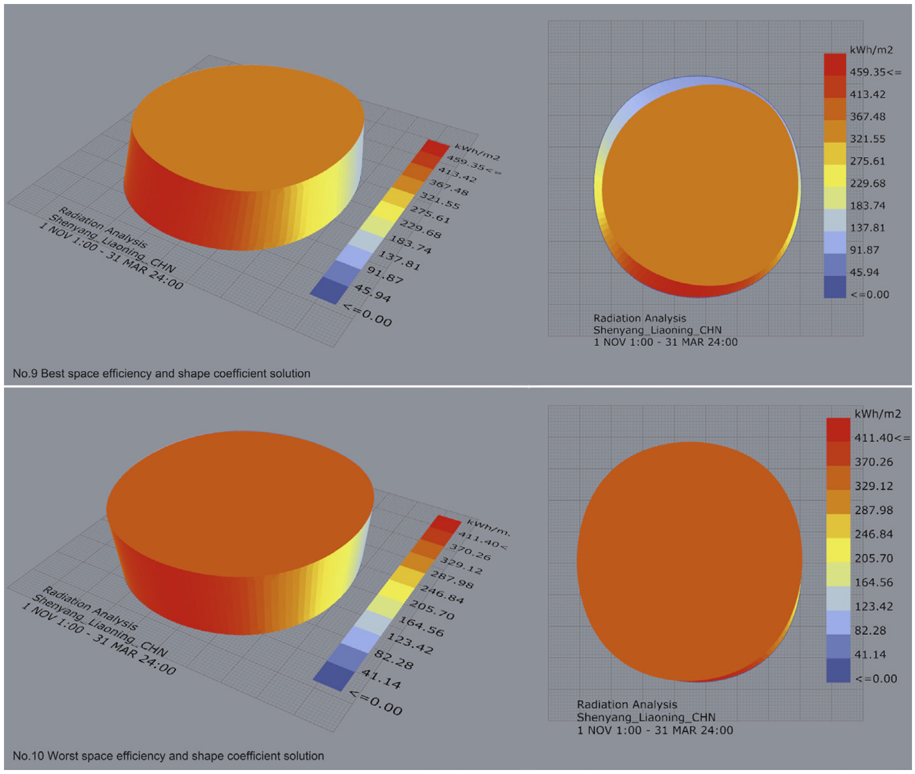


(C) Max space efficiency solution vs. min space efficiency solution



(D) Best solar radiation gain and space efficiency solution vs.
Worst solar radiation gain and space efficiency solution

Fig 8. *(continued)*



(E) Best space efficiency and shape coefficient solution vs.
Worst space efficiency and shape coefficient solution

Fig 8. *(continued)*

two optimizing objectives. The solutions with the best or worst performances in total solar radiation are the solutions with the maximum or minimum products of the total solar radiation and shape coefficients. Therefore, the final ten chosen characteristic solutions' objectives and variables are shown in Table 2, and their shapes are shown in Fig. 8 in pairs for comparison. All the base control-point coordinates are certain and stay at the upper domain, as predicted above; therefore, their values are not listed in the table.

The maximum total solar radiation value of the optimal solutions is 2245062.58 kW h, which is 53% more than the 1462465.36 kW h value of the reference building. The minimum value of the optimal solutions is also nearly 30% more than that of the reference building. These results indicate that the free-form building has a much better performance in solar radiation gain than a regular cube-shaped building. The minimum shape coefficient value of the optimal solutions is 0.1121, which is nearly 20%less than the 0.14 value of the reference building. Therefore, it is shown that the optimized free-form building will get a more effective shape and have a better energy-saving performance. The maximum shape coefficient value of the optimal solutions is also 15%less than that of the reference building. After optimization, the space efficiency values of optimal solutions are all more than 95%. Obviously, the optimization is effective and successful.

Octopus can create 3D models of each solution for visual feedback. Therefore, every optimal shape of the case building on the Pareto frontier can be shown to assist designers in determining the final design solution that will be built in reality after the visual simulation, as predicted above.

5. Conclusion

Architectural design is essentially a process of seeking the best solution based on many factors. Designers need to consider various optimization objectives and to achieve a balance among them. When the optimization objectives are complex and contradictory, it is difficult to find true optimal solutions with only human judgement and experience. In this paper, the shape optimization of free-form buildings in severe cold zones needs to achieve better balances of the three objectives: solar radiation gain, shape coefficient and space efficiency. It must be simulated using digital technologies, such as parametric modeling, building performance simulation and multi-objective genetic algorithm optimization. To integrate these technologies and to increase the efficiency of the design, we provide a method with a "Modeling–Simulation–Optimization" framework. Through this method, parametric modeling is used for generation, and it makes dynamic and precise adjustments of the shape of free-form buildings. The simulation and calculation processes for solar radiation, shape coefficients and space efficiency are performed on the same parametric platform to avoid the errors and risks of data exchanges between different software. A multi-objective genetic algorithm is used to optimize the shape, to generate a Pareto frontier, and to provide several solutions that meet the three objectives, which allows the designer to choose based on their requirements or interests. All these processes work on a common platform and make the optimization more efficient and accurate.

To demonstrate the feasibility of the proposed method, a case study is conducted to optimize the shape of a community centre building in Shenyang, China. After 100 iterations, 84 non-dominated solutions are generated. Compared with the cube-shaped reference building, the maximum total solar radiation value of the optimized free-form building increases by 53%, and the minimum shape coefficient value has a reduction of nearly 20% with a decrease less than 5% of the space-efficiency value. The results indicate that the optimized free-form building has a much better performance in solar radiation gain and shape coefficient value, with only a slightly negative effect on space efficiency.

The conventional optimization of building shapes focuses primarily on simulating building performance; building space usage is rarely a concern. The proposed method follows the basic process of architecture design; it can find solutions that meet the requirements of solar radiation gain, energy saving and space usage simultaneously. This reveals the possibility that the proposed method can be used in real architectural design to solve practical optimization problems.

It is important to note that this paper provides a specific method; other architectural design-optimization problems may require further research. For example, the paper considers only solar radiation gain as the building-performance objective, shape coefficient as the shape objective and space efficiency as the space objective. Other objectives, such as sunlight hours, thermal performance, natural ventilation, and views, require further research.

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