Energy-saving analysis and optimization of shape design elements of high-rise residential buildings in cold regions

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Abstract. Under the background of the current national regulations and the goal of "double carbon", it is necessary to start from the shape design of high-rise residential buildings in cold regions to reduce building energy consumption. This study summarizes the key elements of high-rise residential shape design in cold regions through field research and data collection, and uses Grasshopper platform to simulate energy consumption to explore the influence of plane form, building height and plane size on building energy consumption. Based on the weight order of shape design elements, the research results show that the rectangular plane form with a building floor height of 3m, a building floor of 18 floors, a plane length of 67m, and a plane width of 12.1m is the most energy-saving design choice for high-rise residential buildings in cold regions. Through case verification, the energy saving rate of the optimized house is 5.5 % higher than that of the original house, which verifies the feasibility of energy saving optimization of shape design. The research results can provide some reference for the shape design of future high-rise residential buildings in cold regions.

Keywords: Cold region, High-rise residential buildings, Shape design.

1 Introduction

In recent years, with the rapid development of China' s economy and society, energy demand is increasing. According to statistics, the energy consumption and carbon emissions of residential buildings in China account for about 60% of the total carbon emissions of energy consumption in the operation stage of buildings, among which high-rise residential buildings occupy an important position in urban buildings [1]. With the introduction of the dual carbon target, building energy conservation and emission reduction has become an important task in today' s construction industry. Especially in cold and cold regions, building energy consumption continues to rise due to increased heating demand in winter. Therefore, improving building

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performance and reducing building energy consumption in cold regions are the key ways to achieve the dual-carbon goal in the construction field.

For the energy-saving design of buildings in different thermal climate zones, the specification of envelope structure parameters, indoor environment parameters, and building energy efficiency index limits are on the one hand [2]. In the scheme design stage, controlling building shape design parameters such as plane size, building height and plane form is an effective measure to reduce building energy consumption. Some scholars have carried out relevant research on the energy-saving design of residential shape. For example, Li, J. [3]studies have shown that the most energy-efficient building height in cold regions is 99 m. Feng, X.P. et al. [4]pointed out that reducing the shape coefficient is beneficial to improve the energy saving effect. Taking Ningbo as an example, Ma, Y.L. [5]analyzed the influence of the number of layers, shape coefficient and building area on energy consumption, and put forward the energy-saving design strategy of buildings in hot summer and cold winter area.

The above research results are inconsistent with the current national regulations [6]. However, most of them point out that in the energy-saving design of building shape in cold regions, the plane shape should be considered first, followed by the building height, and finally the plane size should be determined [7]. In view of this conclusion and the height limit of residential buildings, it is of great significance to optimize the design parameters of residential shape for the energy-saving design of high-rise residential buildings in the future and to achieve the goal of near-zero energy consumption of residential buildings.

2 Methodology

This research is divided into three main parts: (a) select the local high-rise residential buildings in Jinan to investigate the most relevant body shape design elements for statistical analysis; (b) Grasshopper is used to simulate energy consumption and analyze the relationship between various elements and building energy consumption; (c) Summarize the energy-saving shape design parameters adapted to cold regions and select actual projects for case verification.

2.1 Studied region

Jinan is located in the central and western part of Shandong Province, China. It belongs to the cold B area in China' s thermal design division. The average annual temperature is 13.6°C, the highest monthly average temperature is 27.2°C, and the lowest monthly average temperature is 3.2°C. The average annual precipitation is 614.0mm, and the annual sunshine hours are 2616.8h. Jinan has 105-120 days in summer, generally from late May to early September, and 136-157 days in winter, generally from early November to late March of the following year. Buildings in cold regions should meet the requirements of heat preservation in winter and heat protection in summer [8].

2.2 High-rise residential plane form

Building plan design is closely related to building shape design. The plane form of residential buildings is not as free as the shape design of public buildings due to the limitation of house type and use function. The survey statistics show that the plane layout of high-rise residential buildings is mostly plate type. In order to simplify the calculation, the planes of residential are simplified. The highest proportion is the rectangular plane and the “convex” plane. Standard floor plane forms are shown in **Fig. 1**.

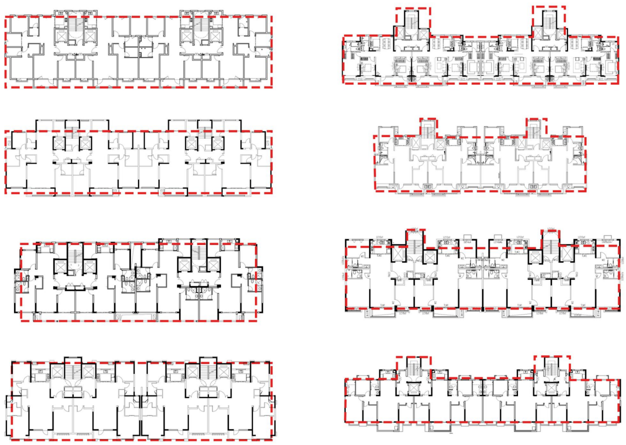

Fig. 1. Standard layer plan forms.

2.3 Building height

The building height is mainly composed of two parts: the number of building layers and the height of building layers. Before the introduction of the state’ s residential height limit regulations, most of the existing high-rise residential buildings reached more than 18 floors. However, the number of layers of the most energy-efficient building in the cold region obtained in previous studies is 33 layers, which is not suitable for the shape design of high-rise residential buildings in the future. In this study, high-rise residential buildings with 18 floors and below 18 floors were selected, and the number of floors was mainly concentrated in 9-18 floors.

The survey found that most of the building floor height are 3m. According to 4.1.2 of *Project Code for Residential Building (draft for comments)* issued in 2022[9], it is preliminarily determined that the floor height of high-rise residential buildings in cold areas is 3m. The statistics are shown in **Fig. 2 and Fig. 3**.

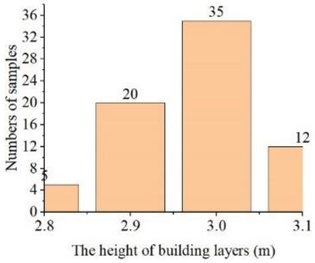

Fig. 2. The number of building floors.

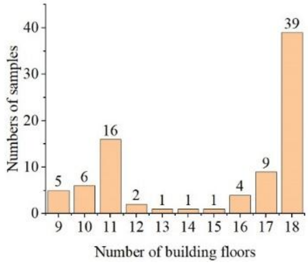

Fig. 3. The height of building layers.

2.4 Building plan size

For the rectangular plane, the building plane size is mainly composed of the length of the house type, the width of the house type and the number of units. According to the statistics of the survey results, the high-rise residential buildings in Jinan are mainly composed of 2 units. Based on the statistics of the length and width of the two-unit row residential buildings below 18 floors, it is found that the length of the building plane is mainly concentrated in the range of 40.6-52.6m, accounting for 54.8%; the width of the building plane is mainly concentrated between 10.3-15.1m, accounting for up to 61.9%. The survey data is shown in **Fig. 4**.

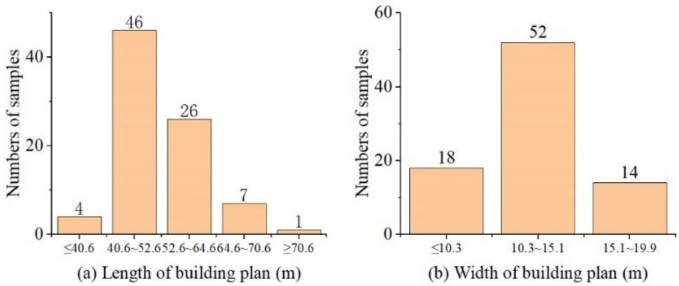

Fig. 4. Building plan length and width statistics.

3 Building energy consumption simulation

3.1 Simulation software selection and parameter setting

In this study, Ladybug Tools plug-in of Rhino Grasshopper platform was used to simulate energy consumption. Combined with Ladybug, Honeybee, and other modules, Energyplus, Radiance, Openstudio and other comprehensive simulation of building energy consumption to ensure the accuracy of data.

The thermal design parameters of the envelope structure of high-rise residential buildings are set according to *Technical standard for nearly zero energy buildings*

(GB/T 51350-2019) and actual projects [2]. The heating and cooling season is set according to Zheng, Z.Y. [10]. The heating season is 1.1-3.31, 10.29-12.31, a total of 154 days, and the cooling season is 6.12-8.22, a total of 72 days. The parameters such as indoor environmental parameters and operating parameters were selected from *Technical standard for nearly zero energy buildings (GB/T 51350-2019)*. Taking the energy consumption per unit building area as the evaluation index, the unit is kWh/m^2, which reflects the energy consumption intensity of high-rise residential buildings.

3.2 The relationship between building plane form and energy consumption

Based on the study of Zhang, H.B. [7], the influence of building shape design parameters on energy consumption is ranked as follows: plane form > building height > plane size. Firstly, the most energy-efficient plane form of high-rise residential buildings is determined to provide a plane form basis for other subsequent parameters. The building plane area is used as a restrictive index. The building height is uniformly determined to be 18 floors, and the building orientation is north-south. The energy consumption simulation calculation of rectangular and "convex" high-rise residential buildings with the same standard floor area, the same building floor height and the same building floor is carried out. The results show that the energy consumption per unit area of the rectangular plane is 38,939 kWh/m^2, and the energy consumption per unit area of the "convex" plane is 41.451 kWh/m^2. It can be seen that the rectangular plane form of two units is more energy-saving.

3.3 The relationship between building height and energy consumption

Based on the fact that the rectangular plane form in 3.2 is determined as the energy-saving plane form, the relationship between building height and energy consumption is further explored. The 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 layers are used as the variables of the number of building layers, and the height of the building layer is taken as a fixed value of 3.0m. Grasshopper is used to simulate the relationship between building height and energy consumption under different plane sizes. When the building plane width is fixed at 12.1m, and the plane length is 40.6m, 43.6m, 46.6m, 49.6m, 52.6m, the change trend of residential energy consumption with the number of floors is shown in **Fig. 5.**

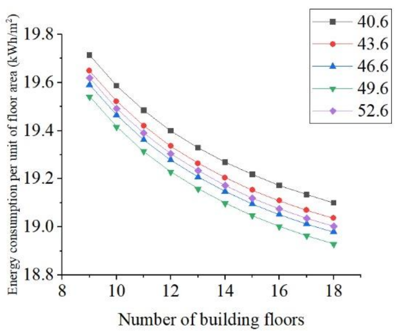

Fig. 5. The relationship between building floors and energy consumption.

It can be seen from the curve change trend that when the number of building layers increases from 6 to 18, the total energy consumption per unit area first decreases and then tends to be gentle. It can be determined that the number of building layers is 18, the building height is 3.0m, and the building height is 54m, which is a reasonable energy-saving shape design parameter for high-rise residential buildings in cold regions.

3.4 The relationship between building plane size and energy consumption

From the conclusions obtained in 3.2, it can be determined that the rectangular plane is an energy-saving plane form adapted to the climatic characteristics of cold regions. The determination of the energy-saving plane form has guiding significance for the plane design of the house to a certain extent, but it cannot determine the plane size. Therefore, the quantitative relationship between plane size and energy consumption still needs to be further studied.

According to the survey results in 2.2.3, the length range of high-rise residential plane is set to 40.6-52.6m, and the width range of building plane is set to 10.3-15.1m. The width of the building is controlled by a single variable, and the value is taken every 1.2m step in the width range. The energy consumption when the plane length changes is simulated by software (**Table 1**).

Table 1. Building energy consumption changes with building length and width.

Length (m)	Energy consumption per unit of floor area (kWh/m^2)								
	Width: 10.3m	10.9m	11.5m	12.1m	12.7m	13.3m	13.9m	14.5m	15.1m
40.6	20.101	19.957	19.828	19.100	18.995	18.901	18.815	18.738	18.666
41.8	20.074	19.929	19.801	19.073	18.968	18.874	18.789	18.711	18.640
43.0	20.048	19.904	19.775	19.048	18.955	18.849	18.764	18.686	18.615
44.2	20.024	19.879	19.751	19.024	18.930	18.825	18.740	18.662	18.591
45.4	20.001	19.853	19.728	19.001	18.907	18.803	18.717	18.640	18.568
46.6	19.978	19.834	19.706	18.979	18.875	18.781	18.695	18.617	18.546
47.8	19.958	19.814	19.686	18.959	18.855	18.762	18.676	18.598	18.526
49	19.938	19.794	19.666	18.940	18.836	18.742	18.656	18.578	18.506
50.2	19.919	19.775	19.647	18.921	18.817	18.724	18.638	18.559	18.487
51.4	19.901	19.757	19.629	18.904	18.800	18.706	18.620	18.542	18.470
52.6	20.024	19.874	19.740	19.002	18.894	18.795	18.705	18.621	18.544

Using SPSS software to estimate the relationship between the building plane length and the energy consumption per unit area, the results show that R^2 value in the quadratic function is higher than other functions, and the fitting degree is better **(Table 2**). That is to say, when the building height and the building plane width are constant, the relationship between the building plane length and the energy consumption per unit area is a quadratic function.

Table 2. Summary of curve estimation.

Equation	F	Statistical significance	R^2
Linear	61.565	<0.001	0.764
Logarithmic	67.558	<0.001	0.780
Quadratic	50.552	<0.001	0.849
Compound	61.544	<0.001	0.764
Power	67.507	<0.001	0.780
S Curve	73.363	<0.001	0.794
Growth	61.544	<0.001	0.764

When the building plane width Y is 10.9m, 12.1m, 13.3m, 14.5m, the functional relationship between the building plane length X and the energy consumption per unit area E is shown in **Table 3**. The fitting degree R^2 of each function is greater than 0.83, that is, more than 83% of the relationship between energy consumption per unit area and length X can be explained by the equation in Table 3.

Table 3. The functional relationship between energy consumption and building length.

Width (m)	The function of total building energy consumption E (kWh /m^2) and length X (m)	R^2
Y=10.9m	$E=0.001X^2-0.151X+23.692$	0.843
Y=12.1m	$E=0.001X^2-0.136X+22.489$	0.879
Y=13.3m	$E=0.001X^2-0.128X+22.111$	0.897
Y=14.5m	$E=0.001X^2-0.121X+21.788$	0.915

The above function relationship image is drawn in the same coordinate system, as shown in **Fig. 6**. It is found that when the building width Y increases from 12.1m to 15.1m, the function image moves up and left in turn. The minimum value of building energy consumption is on the function image with width Y=12.1m, and at the lowest point X=67m. From the above data simulation and quantitative analysis, it can be determined that the plane length of 67m and the plane width of 12.1m are reasonable building energy saving plane sizes in cold regions.

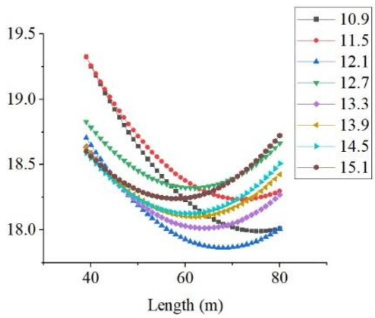

Fig. 6. The relationship between building length and energy consumption.

4 Results and discussions

4.1 Energy-saving optimization of building shape design

In the shape design of high-rise residential buildings, the weight of the influence of building shape design parameters on energy consumption should be analyzed first, that is, plane form > building height > plane size. By exploring the relationship between the relevant parameters of body design and energy consumption, the corresponding conclusions can be drawn. In terms of plane form, high-rise residential buildings in cold regions should give priority to regular rectangular planes to reduce the change of building shape, thereby reducing the external surface area of the building in contact with the outdoor atmosphere and reducing the heat dissipation area of the enclosure structure. In addition, combined with the current national regulations on the number of residential floors, after determining the floor height, when the number of floors is 18, the energy consumption is the lowest. For building plane size, by quantifying the relationship between building plane length and width and building energy consumption, it is determined that the plane length of energy saving in cold regions is 67m and the plane width is 12.1m.

4.2 Case verification

Case overview. In this case, the 3# building of the World Trade Center is selected. The community is located in Huaiyin District of Jinan City, with a total of 7 residential buildings, including 10-storey and 18-storey high-rise buildings. The 3# building was built in 2021, with one floor underground and 10 floors above the ground. The building is 3.0m high and facing north and south. The building is a plate "convex" shaped house with two units. The total area of the building is 8070.4 m^2, the standard layer area is 807 m^2.

Energy-saving optimization simulation analysis. On the basis of the case, the building shape is simplified to a "convex" shape, which is convenient for subsequent calculation and comparison. According to the building parameters, the building is modeled in Grasshopper. The enclosure structure practices and parameters are the same as 3.1 settings.

According to the energy-saving shape design parameters of high-rise residential buildings, the building plane form is transformed from "convex" shape to rectangular shape while keeping the standard floor area unchanged. The overall number of floors of the building is increased from 10 to 18, the height of the floor is maintained at 3.0m, and the total height is 54m. The standard floor area of the building is about 810 m^2, and the length of the rectangular plane is 67m, and the width of the plane is 12.1 m. The building before and after the adjustment are shown in **Fig. 7**.

Through the Ladybug plug-in in Grasshopper, the energy consumption simulation shows that the energy consumption per unit area of the optimized building is 18.731kWh/m^2, which is 5.5% higher than that of the original building (19.829kWh/m^2). From the simulation results of energy consumption, it can be seen that optimizing the shape parameters such as plane form, building height and plane size of buildings can effectively reduce building energy consumption.

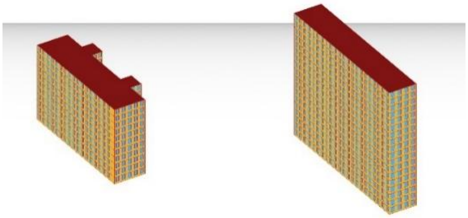

Fig. 7. Building models (left: before optimization; right: optimized).

5 Conclusion

Through the investigation of the current situation of energy-saving design of residential buildings, the Grasshopper platform was selected as a simulation calculation tool to deeply explore the relationship between the shape design parameters of high-rise residential buildings in cold regions and building energy consumption. The shape design of residential buildings is optimized. The main results include:

(1) Through field research and data collection, understand the current situation of energy-saving design of high-rise residential buildings in cold regions and summarize the existing problems of residential buildings. Collect and sort out the data of various body design elements of high-rise residential buildings in Jinan, and statistically analyze the value range of various elements.

(2) Based on the analysis results of the influence weight of shape design elements: plane form > building height > plane size, the relationship between plane form, building height, plane size and energy consumption is analyzed, and the quantitative relationship between plane size and energy consumption per unit area is established. Finally, the image is drawn. Combined with the current residential regulations of the state, the shape design elements of energy-saving high-rise residential buildings suitable for cold regions are determined, that is, rectangular plane, building layer height 3m, building layer 18 layers, building plane length 67m, plane width 12.1m is the most energy-saving high-rise residential shape design parameters in cold regions.

(3) Compared with the original building, the optimized building energy saving rate is 5.5%, which verifies the feasibility of building energy-saving shape design parameter optimization.

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