INFLUENCE OF PLAN SHAPES ON ANNUAL ENERGY CONSUMPTION OF RESIDENTIAL BUILDINGS

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ABSTRACT

The article presents a new methodology for optimising building plan shapes which are from the actual constructions to improve the annual building energy performance for residential buildings. Moreover, the study addresses an important issue concerning the identification and the setting of a set of simple and concise variables that can be used during the conceptual design stage of residential buildings.

The annual energy consumption of residential buildings in Tianjin, China, was dynamically simulated using Design-builder software. By collecting a large number of residential design cases, building energy consumption of residential buildings per unit was analysed based on several common plan shapes. The results indicate that, firstly, rectangular residential buildings (the length faces south) have the lowest energy consumption; secondly, with the increase in building height, residential energy consumption decreases and then increases; thirdly, the relationship between the shape factor and energy consumption of residential buildings is uncertain due to the thermal action of solar radiation.

Keywords: building energy consumption, building height, plan shapes, residential buildings, shape factor, solar radiation.

1 INTRODUCTION

As is known to all, energy efficient building design is a complex project in that the concept and awareness of energy efficiency is manifested in many fields of technology, from building shapes and envelope design to the heating and air-conditioning system design, from architectural design to building materials chosen, operating mode management and so forth. But at present, more and more actual projects are focused on the innovation of insulating materials, promotion of energy-saving heating and air-conditioning systems, development of supply modes of new energy resources, etc., in which the energy-saving design in architectural creation was usually neglected. In order to design energy-efficient buildings, the concept of energy saving should be integrated into the design scheme at the stage of scheme creation, otherwise energy efficiency has to be achieved by improving the thermal performance of the building envelope during the later stage of the design.

In colder regions of China, the insulating performance of buildings in winter is the focus of energy savings. Thus, the area of building facade should be minimised to reduce heat loss in winter, which requires the building shape to be simplified and the unevenness of the facade to be reduced as much as possible in the architectural design. Therefore, the design of plan shapes during the architectural creation stage is of vital importance in the energy efficient building design in that it is a key step in determining the energy efficiency of buildings.

Many studies [1–6] have been conducted on energy efficient design of plan shapes, and a definite conclusion has been made on the relationship between different plan shapes and energy consumption, as shown in Table 1 [7], which can guide architects in the energy-saving design at the stage of scheme creation. Song Dexuan and Zhang Zheng [8] studied the relationship between shape coefficient, plan shape, orientation and the energy consumption of buildings. The regularity of changes in energy consumption was proposed as a united descending column,

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Table 1: Relationship between plan shapes and energy consumption (Taken from Wang Lixiong's works [7]).

Plan shapes	Square	Rectangle	Thin rectangle	L-shape	Rectangular-ambulatory plan	U-shape
Shape factor	0.16	0.17	0.18	0.195	0.21	0.25
Energy consumption (%)	100	106	114	124	136	163

Note: Shape factor is defined as the ratio between the external skin surface area of building and its inner volume. When the energy consumption of square-plan building is defined as 100, the building energy consumptions of other plan shapes are shown in the table.

inversely proportional to height, square limit, L/A replacement. Circular plane was most conducive to energy conservation, when the triangle plane was the worst compared with the square and rectangle plane considering the impact of solar radiation. Weimin Wang [9] developed a methodology to optimise building shapes in plan using the genetic algorithm, where the green building footprint was defined as a multi-sided polygon. Two representation methods, length-angle method and length-bearing method, were compared in terms of their impact on the computational effectiveness and efficiency for multi-objective optimisation with GA. Mechri and Capozzoli [10] identified the design variables that have the most impact on the variation of the building energy performance and to allocate the contribution of each variable to this variation, using the Analysis Of Variance. Then the following aspects had been retained as the most important design variables: shape, envelope transparent surface, outer colour, orientation, external solar shading and mass distribution. For the heating and cooling energy needed assessment, the most significant factors was the envelope transparent surface ratio, and the other factors were less involved. Jerome Henri [11, 12] proposed a new methodology for optimising building and urban geometric forms for the utilisation of solar irradiation using a hybrid CMA-ES/HDE algorithm by RADIANCE, whether by passive or active means. Application of this methodology to three very different examples suggested that the new technology consistently converged towards an optimal solution. Furthermore, with respect to the configurations subjectively chosen to be intuitively well performing, annual irradiation was increased by up to 20%; sometimes yielding highly non-intuitive but architecturally interesting forms.

However, such a conclusion in table 1, in which only the heat consumption of the building in winter is considered, is devoid of a consideration of the effects of solar radiation on building energy consumption and of air conditioning energy consumption on the building in summer. Further, when the relationship between the shapes and the building energy consumption, only simple geometric shapes or the site shape to be considered, but the residential plan shapes in actual constructions are not collected completely to be researched. So that the results of previous studies cannot be directly applied to conceptual design to provide direct help for architects. On the other hand, the previous conclusions do not take into account all factors just like the solar gains, the cooling loads, the heating loads and so on when they did the calculations. In view of this, this study attempts to explore the quantitative relationship between different plan shapes and building energy consumption based on the climate features in cold areas, and the combined effects of solar radiation, heating systems in the winter and air conditioners in summer on building energy consumption. This study takes residential buildings as the research object of which the plan shapes are less than public buildings in order to facilitate experiments.

2 RESEARCH METHODS

Firstly, 89 residential buildings designed by eight large-sized architecture design institutes in Tianjin since 2007 were surveyed in this study, which covered all residential types (Fig. 1) [13, 14]. Common plan shapes (Fig. 3) of residential buildings were categorised (Fig. 2) by examining the design drawings and making an on-the-spot survey, and in accordance with relevant design standards for residential buildings at country level.

Compared to the software "EnergyPlus", DesignBuilder not only can simulate the energy consumption of buildings accurately, but also has a good visual interface for users which is lacked in EnergyPlus [15]. So it was used in this study to calculate the annual building energy consumption, in order to analyse the influence of plan shapes on energy consumption and ultimately to explore the quantitative relationship between different plan shapes and the annual energy consumption.

Based on the difference of shapes, residential buildings can be divided into slab blocks, point blocks and single-family houses. Significant differences exist in the standard plan shapes, which include these three types: the first type is mostly featured by a rectangle, Z-shape and L-shape; the second convex shape, concave shape, cross shape, etc.; and the third more varied plan shapes due to the relatively free design. As is seen from the combining mode of house types, the first type with a smaller depth and larger width receives more solar radiation in winter and better natural ventilation in summer; the opposite is true of the second type, which has the advantage of a smaller indoor-and-outdoor contact area and less heat loss in winter; the third type is superior to the first two in terms of solar radiation and ventilation due to the relatively free design. Thus, different types of residential buildings have inherent differences in energy consumption.

In addition, the slab blocks are commonly seen in multi-storey and middle high-rise buildings; the tower blocks are mostly found in high-rise buildings; and the single-family houses are usually constructed with 3 or less storeys. Different building heights bring about different shape factors, thereby leading to differences in energy consumption.

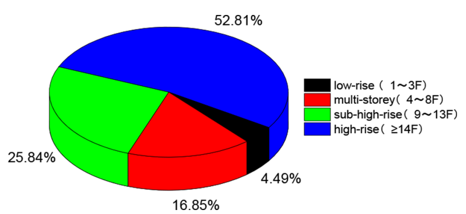

Figure 1: Types of residential buildings.

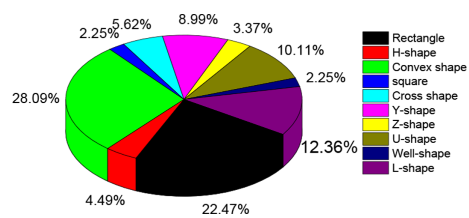

Figure 2: Statistics of different plan shapes.

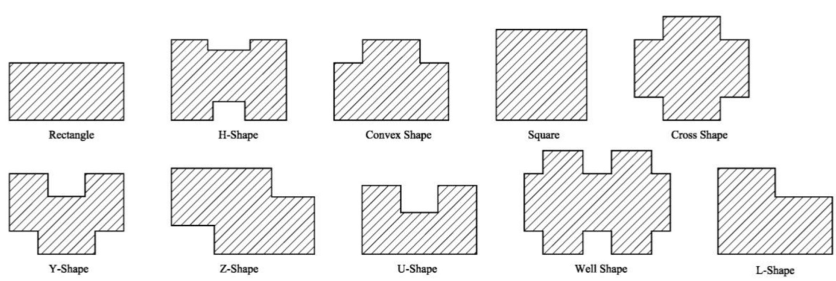

Figure 3: Different plan shapes of residential buildings.

Therefore, the influence of plan shapes on the annual building energy consumption should be analysed at different building heights based on different residential types. Specific research content is as follows:

1. The rectangular, square, Z-shaped and L-shaped slab blocks with 6 and 9 floors were taken as examples to make a simulation analysis of the influence of plan shapes on the annual building energy consumption per unit.
2. The convex, rectangular, H-shaped, cross-shaped, Y-shaped, U-shaped, Z-shaped, square and well-shaped tower blocks with 9, 18, 25 and 33 floors were taken as examples to make a simulation analysis of the influence of the plan shapes on the annual building energy consumption per unit.
3. The rectangular, triangular, circular and square single-family houses with 3 floors were taken as examples to make a simulation analysis of the quantitative relationship between different plan shapes and building energy consumption per unit.

3 RESEARCH OBJECTIVES

The building area determined by the task book is a prescriptive index in residential design, and building models will be established based on the same floor area and different plan shapes during the simulation analysis. The investigation of the status quo of residential construction in Tianjin City reveals that, firstly, the type of housing is mostly two-bedroom or three-bedroom units. Secondly, the tower blocks take the floor of “one elevator and four

Table 2: Simulation experiment design of energy consumption influenced by plan shapes of residential buildings.

Plan shapes of residential buildings		Building height (the storey height=3 m)					
		3 floors	6 floors	9 floors	18 floors	25 floors	33 floors
multi-storey, sub- high-rise and high-rise residential buildings with the floor area of 360 m^2	Convex shape			T	T	T	T
	Rectangle		S	S+T	T	T	T
	H-shape			T	T	T	T
	Cross shape			T	T	T	T
	Y-shape			T	T	T	T
	U-shape			T	T	T	T
	Z-shape		S	S+T	T	T	T
	Square		S	S+T	T	T	T
	Well-shape			T	T	T	T
	L-shape		S	S+T			
Single-family detached houses	Rectangle	H					
	Square	H					
	Circle	H					
	Triangle	H					

Note: S slab blocks T tower blocks H single-family houses suites" as their mainstream form, with the typical floor area mostly being 350 m^2–480 m^2; the slab blocks have different numbers of building units, thus having a greater range of variation in the typical floor area; the single-family houses have greater freedom in design. For comparability of the study, the floor area of residential buildings was chosen to be 360 m^2, the floor sizes were determined as the average values and the storey height was 3 m, based on the results of the survey.

3.1 Envelopes

According to the survey on residential buildings in Tianjin, the envelopes of the model were set as shown in Table 3. The thermal performance of the building envelope meets the requirement of the Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26-2010) [13], and the window to wall ratio was set in accordance with the limits specified in the design standard for energy efficiency. In addition, the shading was not considered in the simulation.

3.2 Activities and lighting

In this study, the occupancy template was chosen correspondingly for each room based on different functions. The interior lighting power density (LPD) was set, respectively, for different functional spaces in accordance with the provisions in the Standard for Daylighting Design of Buildings (GB50033-2013) [16] which works for China; the time schedule was chosen, respectively, for the open time of light apparatuses based on different functions; and ceiling lamps were mainly used in the indoor lighting system.

3.3 Heating and cooling

In accordance with relevant design standards for energy efficiency of residential buildings in Tianjin City and other parts of the country, the heating time lasted for 4 months starting from 15 November each year, and the "central heating using water: radiators" was used in the heating system with the boiler efficiency of 70%; independent air conditioners used in the air conditioning system were set to turn on when the outdoor temperature exceeded 30°C; the

Table 3: Set of envelopes of the model.

Envelope	Construction	Heat transfer coefficient ($W/m^2 \cdot K$)
External Walls	200 mm Reinforced concrete 50 mm XPS Extruded Polystyrene	0.56
Flat Roofs	100 mm Reinforced concrete 70 mm XPS Extruded Polystyrene	0.40
External Windows	Aluminium window frame (with thermal break), Low-E glasses (9 mm + 12 mm Air + 9 mm), emissivity <0.2	1.70

indoor calculating temperature was set for 18°C and 26°C in winter and summer, respectively. The air circulation ratio was 0.5 time/hour in winter and 1 time/hour in summer.

3.4 Others

In order to reduce the time of computerised simulation and simplify the energy consumption simulation process, the model was simplified and an ideal model was proposed. The separation of indoor space, the influence of non-heating staircases on the building's overall energy consumption, and the unevenness of the balcony or staircase protruding from the facade were not considered in the ideal model.

4 RESEARCH RESULTS

4.1 Influence analysis of plan shapes of slab blocks on energy consumption

Based on the survey results of common floor sizes of residential buildings and the principle of convenience in simulation calculation, if the depth of the rectangular slab blocks covering the floor area of 360 m^2 is 12 m which is the average value of the survey, the floor size is 12 m × 30 m. The floor size of other plan shapes is shown in Fig. 4. Considering the influence of solar radiation and the wind throughout the year, the annual energy consumption of south-facing residential buildings of different plan shapes at different heights was calculated in the simulation analysis (Fig. 5) when the window to wall ratio and other parameters remained unchanged.

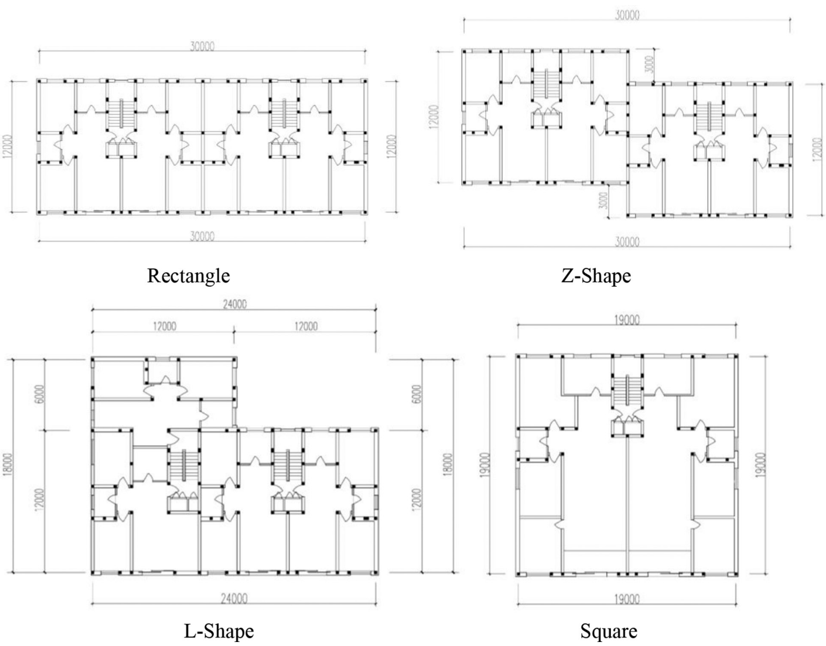

Figure 4: Floor sizes of slab blocks of common plan shapes (The orientation is up North, down South).

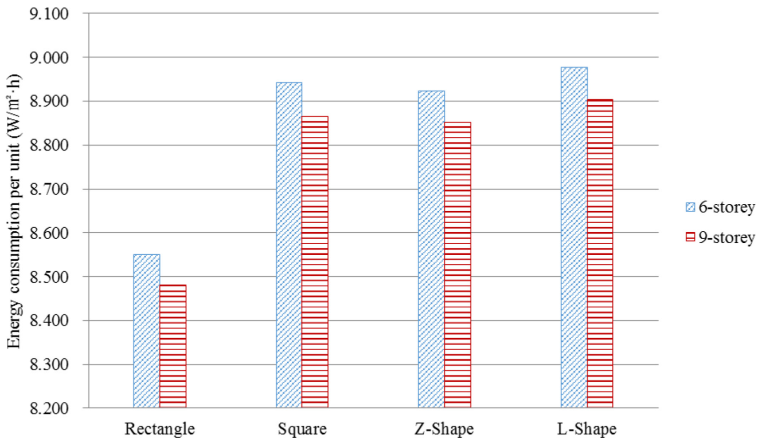

Figure 5: Annal energy consumption value of slab blocks per unit.

The simulation result indicates that rectangular slab blocks have the lowest annual energy consumption, followed by Z-shaped and square ones, and L-shaped ones have the highest. In addition, with the increase in the number of building storeys, the annual energy consumption value of these buildings decreases.

4.2 Influence analysis of plan shapes of tower blocks on energy consumption

The typical floor of tower blocks is shown in Fig. 6. Floor sizes were determined based on the different plan shapes, taking 360 m^2 as the standard area.

The simulation result, as shown in Fig. 7, indicates that annual energy consumption of the rectangular tower blocks is the lowest, while that of other plan shapes is listed in an ascending order: Z-shape <square <convex shape <H-shape <well-shape <Y-shape <U-shape <cross shape. In addition, with the increase in the number of building storeys, energy consumption falls and then rises, with the inflection point occurring above the 18th storey.

4.3 Influence analysis of plan shapes of single-family houses on energy consumption

The single-family houses in China generally cover a building area of 250 m^2–500 m^2. For convenience of simulation in this study, the building area of the model was 300 m^2 and that of single-storey residential buildings, 100 m^2. Due to the unclear directionality of triangles and circles, the window to wall ratio cannot be set in accordance with the design standard for energy efficiency of residential buildings. In order to reduce the errors in the simulation, the window to wall ratio of all models with all orientations was uniformly set to be 0.3, the minimum limit in the design standard for energy efficiency, and the external window was designed to be 1.8 m × 1.5 m (width × height) in size.

The simulation result, as shown in Table 4, indicates that the annual energy consumption of rectangular single-family houses is the lowest, while that of other plan shapes is listed in an ascending order: square < circle < triangle. The single-family houses differ from the slab-type and tower-type ones in the quantitative relationship between different plan shapes and energy consumption, due to the differences in the typical floor area and window to wall ratio.

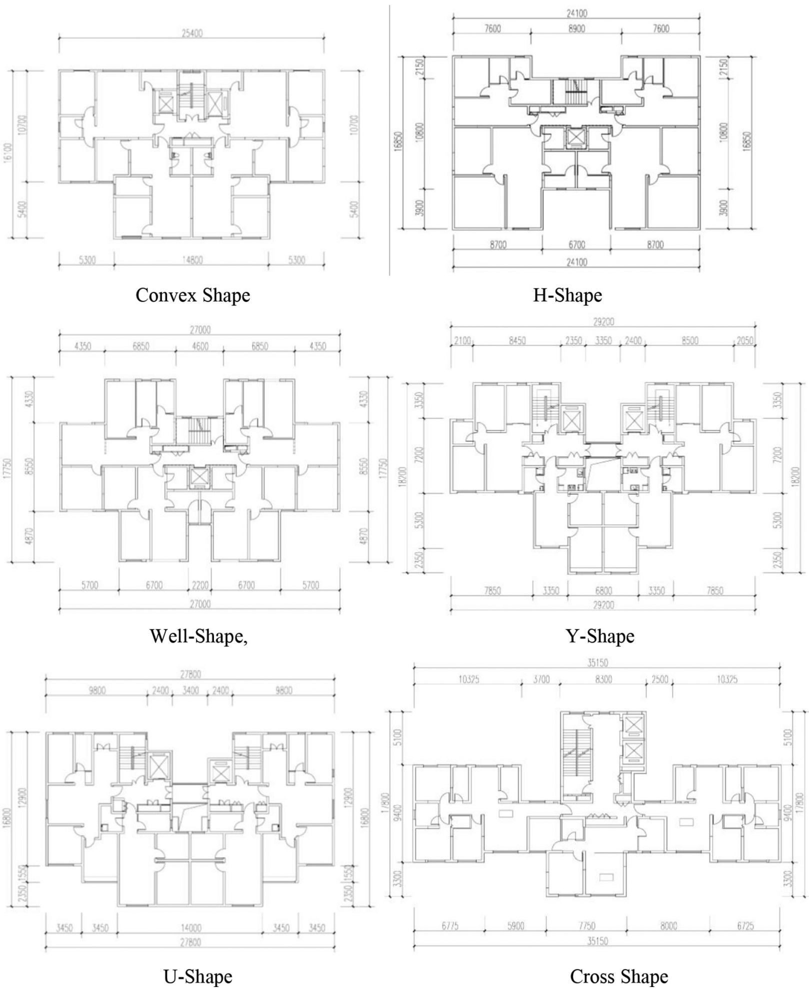

Figure 6: Different planes of tower blocks (The orientation is up North, down South).

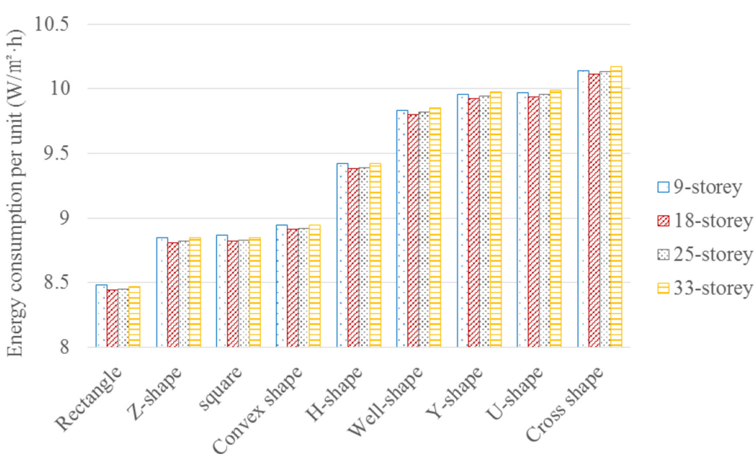

Figure 7: Annal energy consumption value of tower blocks per unit.

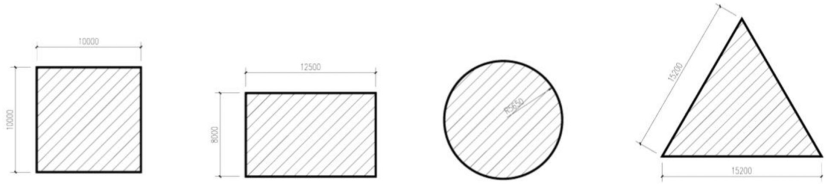

Figure 8: Planes of single-family houses.

Table 4: Energy consumption of low-rise single-family houses of different plan shapes per unit.

Plan shapes	Rectangle	Square	Circle	Triangle
Shape factor	0.511	0.501	0.456	0.557
Building energy consumption per unit	98.2%	100%	100.6%	102.9%

5 DISCUSSION

5.1 Relationship between shape factor and energy consumption of slab-type residential

Previous studies revealed that residential energy consumption increased with the shape factor, but the experimental result in this study, as shown in Fig. 9, indicates that the variation trend of shape factors of slab blocks of four different plan shapes and of annual energy consumption is inconsistent with the previous research conclusion in Table 1.

As shown in Figs 10 and 11, the influence of plan shapes on the heating energy consumption of slab blocks in winter is basically the same as that on the annual energy consumption (Fig. 4). However, the air conditioning energy consumption of square slab blocks in summer is the lowest, while that of L-shaped ones is the largest. The difference in annual energy consumption among different types of residential buildings is due to the differences in plan shapes, window to wall ratio, heat gains through solar radiation from the external window into the indoor space, and heat loss through the external window.

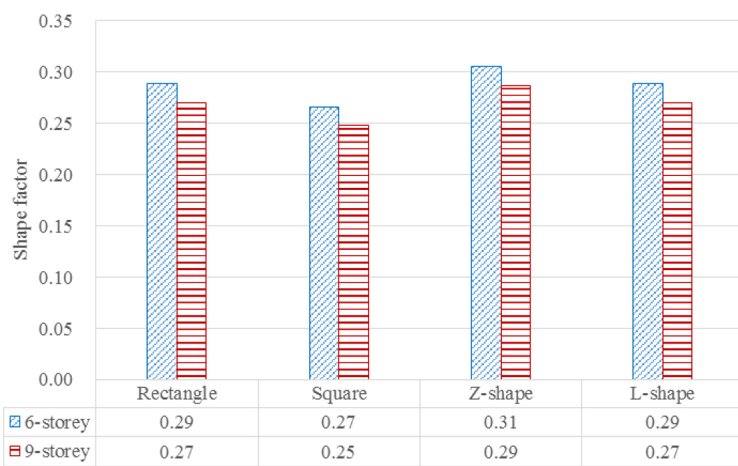

Figure 9: Comparison of shape factor among slab blocks of different plan shapes.

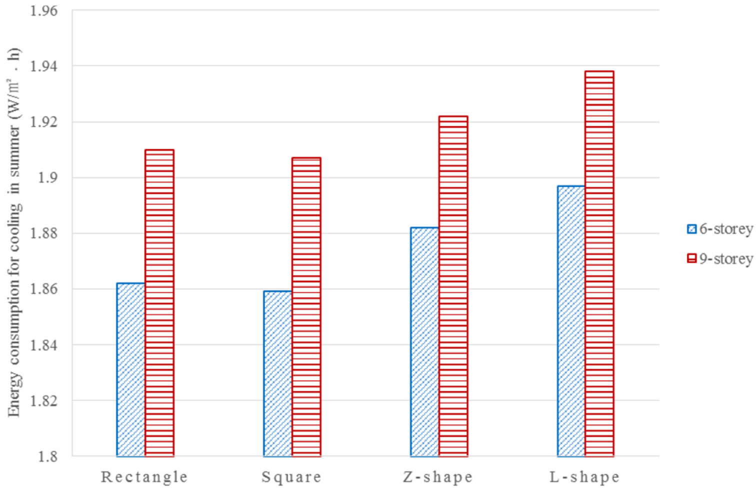

Figure 10: Air-conditioning energy consumption of slab blocks per unit in summer.

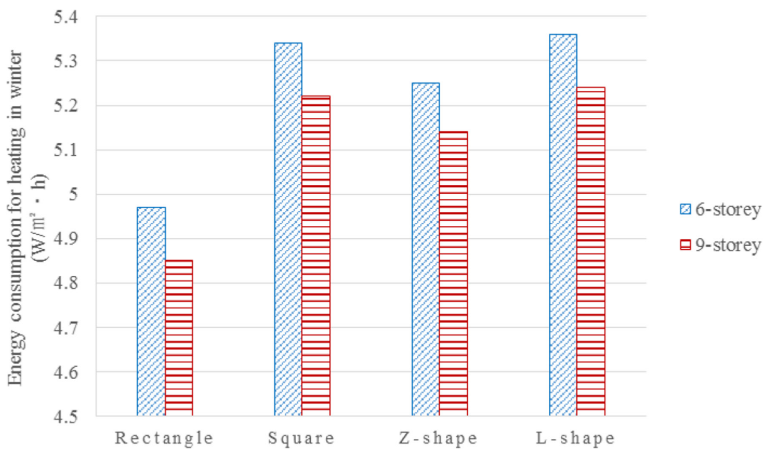

Figure 11: Heating energy consumption of slab blocks per unit in winter.

In order to avoid the influence of heat gains through solar radiation on energy consumption, a simulation analysis was made after removing external windows from all building models. The simulation results, shown in Fig. 12, indicates that the annual energy consumption of the square slab blocks is the lowest without considering external windows, and the influence of different plan shapes of residential buildings on energy consumption is basically the same as that on the shape factor. However, as for the slab blocks with the same shape factor, the annual energy consumption of L-shaped houses is slightly higher than that of the rectangular ones. This is due to the fact that the external walls with different orientations cover different areas, giving rise to differences in heat gains through solar radiation**.** That is, the slightly lower energy consumption of the rectangular slab-type residential results from the larger area that the south-facing external wall covers.

In order to accurately compare the quantitative relationship between all different plan shapes and energy consumption, with reference to Table 1, if energy consumption of the

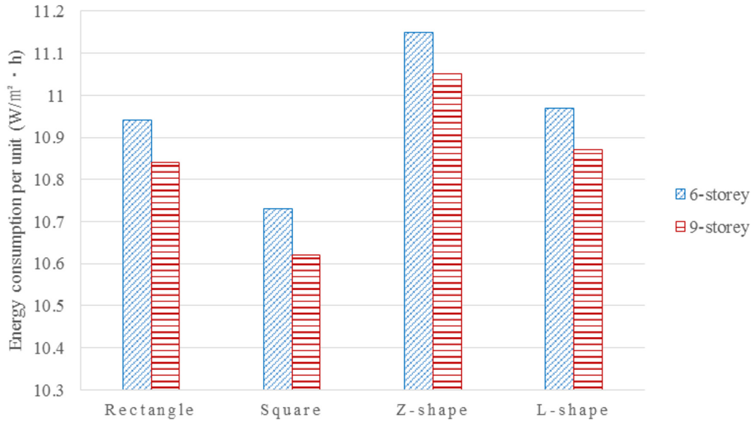

Figure 12: Annual building energy consumption per unit without external window.

Table 5: Comparison of energy consumption among slab blocks of different plan shapes.

Plan shapes	Rectangle	Square	Z-shape	L-shape
Energy consumption of the 6-storey building	95.6%	100%	99.8%	100.4%
Energy consumption of the 9-storey building	95.6%	100%	99.8%	100.4%

square slab blocks is assumed to be 100%, that of other plan shapes with the same typical floor area at the same building height is shown in Table 5.

5.2 Relationship between shape factor and energy consumption of tower-type residential

As shown in Fig. 13, the relationship between the shape factor and energy consumption of tower-type residential buildings of these plan shapes is uncertain. This is due to the fact that the thermal action of solar radiation exerts an influence on the overall building energy

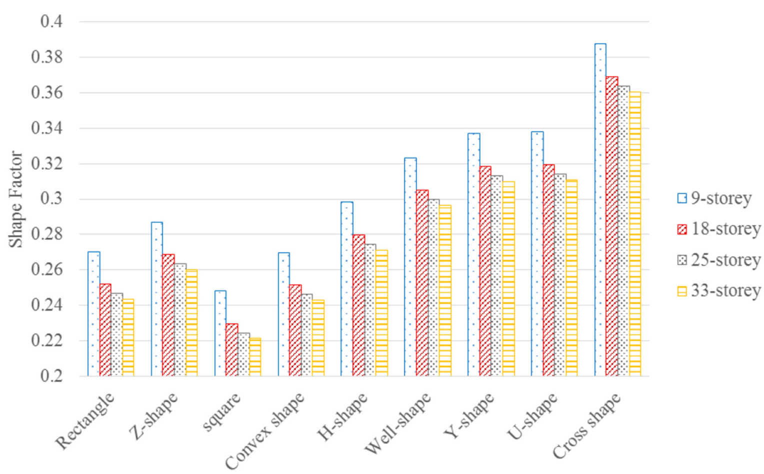

Figure 13: Comparison of shape factor among tower blocks of different plan shapes.

Table 6: Comparison of energy consumption among tower blocks of different plan shapes.

Plan shapes	Rectangle	Z -shape	Square	Convex shape	H -shape	Well -shape	Y -shape	U -shape	Cross shape
Building energy consumption per unit	95.6%	99.8%	100%	100.9%	106.2%	110.9%	112.3%	112.4%	114.4%

consumption, as stated in Section 5.1. Moreover, judging from its computational formula, the shape factor is inversely proportional to the value of the building height; energy consumption is inversely proportional to building height below the 18th storey, but with the increase in the number of building storeys, it is directly proportional to building height. This also proves the limitations of the argument that "residential energy consumption increases with shape factor" in previous studies.

In order to accurately compare the quantitative relationship between all different plan shapes and energy consumption, with reference to Table 1, if energy consumption of the square tower blocks is assumed to be 100%, that of other plan shapes with the same typical floor area at the same building height is shown in Table 6.

6 CONCLUSION

The results indicate that plan shapes of residential buildings exert a significant influence on energy consumption, and the rectangular residential buildings (the length faces south) have the optimal energy-saving effect. Among the slab blocks, tower blocks and single-family houses, the relationship between plan shapes and energy consumption is basically the same, on which the floor area and window to wall ratio have a certain influence.

There are some limitations concerning the relationship between plan shapes and energy consumption in previous studies without considering the influence of heat gains from solar radiation, because such heat gains make a significant contribution to energy savings of residential buildings. Influenced by solar radiation and other climate conditions, the shape factor is not necessarily directly proportional to building energy consumption. The shape factor is inversely proportional to building height, but with the increase of building height, residential energy consumption increases and then decreases, with the inflection point occurring above the 18th storey.

The design of plan shapes of residential buildings is of vital significance to the energy efficient design. Buildings of different plan shapes have different building shapes and facades, which directly affect the heat exchange inside and outside the buildings. Therefore, the design of plan shapes of residential buildings is the first step in energy efficient design, which gives full play to the architects' subjective initiative and allows them to play a major role in the energy efficient design. The selection of relatively energy-efficient plan shapes and a consideration of the influence of the window to wall ratio and other design parameters in residential design will remarkably promote an energy efficient design.

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