Building Simulation

Effect of geometric factors on the energy performance of high-rise office towers in Tianjin, China

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Abstract:	To improve energy efficiency of office buildings in Tianjin, we select a prototypical high-rise office tower as an example and focus on the effect of geometric factors on building energy performance. These factors include the orientation, plane shape, floor area, plane shape factor (the ratio of the plane length to the plane width, only as regardes to a rectangle-shaped plane), floor height, floor number and window-to-wall ratio. The simulation is performed in DesignBuilder, which integrates artificial lighting with instantaneous daylight during the energy simulation process. The geometric factors of the defined prototype are examined in both single-parameter and multi-parameter evaluations. As to the multi-parameter results, the energy saving rate can vary by up to 18.9%, and reducing the floor height is observed to be the most effective means of reducing annual total end-use energy consumption, followed by increasing the plane shape factor and reducing the floor area. The results can serve as a reference for passive design strategies related to geometric factors in the early design stage.
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	change the first sentence: To improve energy saving efficiency of office building in Tianjin, we select high-rise office tower as an example and focus on the effect of geometric factors on building energy performance. to To improve energy efficiency of office buildings in Tianjin, we select a high-rise office tower as an example and focus on the effect of geometric factors on building energy performance. Reply: The authors have taken into account your suggestion, however, we consider it to be more appropriate to change the first sentence to To improve energy efficiency of office buildings in Tianjin, we select a prototypical high-rise office tower as an example and focus on the effect of geometric factors on building energy performance. 2. There are too many references in Chinese. Authors need to reduce them to be less than 3-5. Reply: The authors tried to reduce Chinese references as you suggested. There were totally 14 Chinese references in our 3th revision. Now the number is reduced to 8. One major reason why we failed to meet your requirement is that there are 7 cites regards to local standards and statistical yearbook which is quite essential to our research. So, we considered it may be more suitable to keep them. 3. Please consider to cite one or two Building Simulation journal papers if relevant. For your reference, the contents of 2015 and 2016 are attached, which can be accessed by following the provided link at the bottom of this email. Reply: The authors have taken into account Building Simulation journal papers in the beginning. We have cited “Liu L, Lin B, Peng B (2015). Correlation analysis of building plane and energy consumption of high–rise office building in cold zone of China. Building Simulation, 8: 487–498.”.

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Abstract

To improve energy efficiency of office buildings in Tianjin, we select a prototypical high-rise office tower as an example and focus on the effect of geometric factors on building energy performance. These factors include the orientation, plane shape, floor area, plane shape factor (the ratio of the plane length to the plane width, only as regards to a rectangle-shaped plane), floor height, floor number and window-to-wall ratio. The simulation is performed in DesignBuilder, which integrates artificial lighting with instantaneous daylight during the energy simulation process. The geometric factors of the defined prototype are examined in both single-parameter and multi-parameter evaluations. As to the multi-parameter results, the energy saving rate can vary by up to 18.9%, and reducing the floor height is observed to be the most effective means of reducing annual total end-use energy consumption, followed by increasing the plane shape factor and reducing the floor area. The results can serve as a reference for passive design strategies related to geometric factors in the early design stage.

Keywords:

Energy performance; Geometric factors; High-rise office towers; Tianjin

1. Introduction

The building sector is constantly expanding in China, with the consequence of energy and environmental crisis. The large energy consumption of office buildings has been a major concern during the past few years mainly due to two aspects: increasing built area and high energy intensity. Completed building area of office buildings totally amounts to 2.4 billion square meters from 2000 to 2014, which is about 7.1% of total completed building area in China during this specific period (NBSPRC 2001-2015). Public buildings, represented by office buildings, are characterized by an average energy intensity of about 60 kWh/m^2.yr, their energy consumption accounts for 28.7% of total building energy consumption in China (THUBERC 2016). High-rise office towers are one of the fastest growing categories in office building sector especially in major cities such as Tianjin and Beijing. Because of the climatic diversity in China, the passive designs of these buildings and their energy performance may vary a great deal in different climatic zones. China is divided into five thermal design zones according to average temperature in the coldest and hottest month. Tianjin is located in the cold zone which shares an average temperature of 0-10°C in the coldest month, thus buildings require both heating and cooling demand during the whole year cycle (GB 50176-93 1993). In this paper, a prototypical high-rise office tower in Tianjin is considered.

Previous recommendations in design guides published for architects suggest that form does matter to building energy performance (Liu et al. 2009). As far as the early design stage, design variables that influence the building energy performance the most include building shape, window areas, and fabric materials (Granadeiro et al. 2013). Geometric factors related to building shape and window design should be considered carefully to eliminate energy demand without a large increase in capital costs. Architects need rules of thumb about how the energy performance of a building is affected by its geometric factors.

Existing research related to the effect of geometric factors on building energy consumption can be divided into two categories. The first category focuses on establishing a simple numeric indicator or a direct correlation to obtain information about the energy performance of building. Typically, such indicators include the shape coefficient and relative compactness. The second category entails analyzing the impact of morphological design decisions, such as orientation, the plane shape configuration and layout, the window-to-wall ratio and other physical characteristics.

(1) Establishment of a numeric indicator or a direct correlation

To account for the energy implications of the envelope shape of a building, the correlation between the shape coefficient and building heating consumption was assessed (Depecker et al. 2001). The shape coefficient is defined as the ratio of external skin surfaces to the inner volume of the building. The results show that in severe cold and scarcely sunny winters, the higher the compactness of the building (weak shape coefficient) is, the lower the heating energy consumption is. However, this finding cannot be applied in the case of mild climates related to long sunny periods. The impact of the shape coefficient on total energy demand for heating and cooling was taken into account (Premrov et al. 2015). It was concluded that for timber-frame houses in three different European cities, similar guidelines were observed for the total energy demand. To better describe the subjective characteristics of shape compactness, the concept of relative compactness (RC) is introduced, which is derived by comparing the volume to surface ratio of a shape to that of a compact reference shape (sphere or cube) with the same volume (Mahdavi and Gurtekin 2002). The relationship between relative compactness and the simulated heating load of buildings with various shapes, orientations, glazing percentages and glazing distributions was investigated. The results indicate that for Vienna, Austria, the higher the relative compactness is, the lower the heating load is (Pessenlehner and Mahdavi 2003). The shape coefficient and relative compactness seem to capture building geometry well in severe cold and scarcely sunny winters when building thermal performance is considered. However, it fails to correlate with energy demand in the presence of solar heat gains. To overcome the shortcomings of the shape coefficient, a new design indicator named ERED (envelope-related energy demand) was developed by means of thermal balance analysis. The inputs to ERED include the areas of envelope elements, the U-value of envelope materials, the SHGC of windows and site-related parameters (Granadeiro et al. 2013). A simplified analysis tool to predict the effect of building shape on cooling and total (cooling and heating) energy use for office buildings was developed as a function of relative compactness, the window-to-wall ratio, and the glazing solar heat gain coefficient (Ourghi et al. 2007).

The work of Ourghi et al. was extended to include more plane shapes, as well as window areas and glazing types (AlAnzi et al. 2009). As discussed above, the previous literature mainly focused on the influence of the building geometry configuration on building thermal performance, whereas the implications on artificial lighting energy use are neglected.

(2) Impacts of morphological design decisions on building energy consumption

Relevant existing studies focus on searching for preferable individual geometric configurations or a combination of the considered factors (the optimal approach). Such factors as the orientation; the plane shape factor (Florides et al. 2002; Aksoy and Inalli 2006); the plane shape configuration and layout (Liu et al. 2015); and the window-to-wall ratio (Persson et al. 2006; Goia 2016; Fasi and Budaiwi 2015) are analyzed. The influence on daylight and, accordingly, lighting and total energy use has become the subject of dedicated research activities only in recent years. Based on the analysis of influence coefficients of several alternative design options in terms of a base case, important design parameters related to building energy performance are identified for an office building in Hong Kong. Annual building energy consumption is one of the main sensitivity analysis outputs, while daylighting utilization is not taken into consideration (LAM and HUI 1996). A sensitivity analysis is performed to investigate the important design parameters among the 21 selected factors to change in order to reduce the primary energy consumption. The results show that lighting control is one of the two most important parameters (Heiselberg et al. 2009). Thermal and lighting simulations are conducted for different building shapes, glazing areas, and weather files in order to establish their impact on building heating demand and indoor mean illuminance level. Two regression models are obtained with the output heating demand and mean illuminance level respectively. Thermal energy demand and lighting environment are discussed separately in the paper (Catalina et al. 2011). A typical perimeter office room is selected in a case study to investigate the influence of seven passive design parameters on annual lighting, heating and cooling energy. The analysis is under the assumption of a continuously dimmable lighting control system to explore the benefits of daylighting (Shen and Tzempelikos 2013). Geometry factors related to fenestration design, such as window orientation, window to wall ratio, and room width to depth ratio, are considered to find the best combinations of parameters optimizing daylighting and energy savings. (Susorova et al. 2013). Eight cases of typical high-rise office building planes are established in the cold zone of China, including a linear shape plane, polygonal line plane, dot shape plane and plane with an atrium. The results show that a linear plane with traffic space arranged in the north has the lowest energy consumption (Liu et al. 2015). The energy performance of three types of windows in a typical office in hot climate is examined with or without daylight integration, and a significant reduction in the annual building energy consumption is observed with daylight integration (Fasi and Budaiwi 2015). The optimal window-to-wall ratio minimizing the sum of energy use for heating, cooling and lighting in office buildings is found for four European climates. It is demonstrated that conventional ways of thinking are not always true in regards to global considerations of total energy use (Goia 2016).

Researchers have developed parametric simulation tools to evaluate numerous potential designs for the early design stage (Attia et al. 2012; Petersen and Svendsen 2010), as well as to identify optimal solution, such as BEOpt from the National Renewable Energy Laboratory (Christensen et al. 2006) and the DesignBuilder optimization program from the DesignBuilder software (DesignBuilder n.d. 2016). But there are limitations as to performance objectives and available input parameters. Especially in that geometric factors variation may require repeat modeling process (DesignBuilder n.d. 2016). Utilization and linkage of several different tools may be a solution to this problem as described in latest research (Samuelson et al. 2016), which used ArchSim to convert the building model to input files for EnergyPlus to generate exhaustive search results. The exhaustive approach, i.e. simulating all possible design combinations from a discrete search space, is regarded to be suitable for creating design guidelines.

In summary, the influence of geometric factors of buildings in preserving a comfortable indoor environment has previously been related to heating or/and cooling energy use, whereas the implications on artificial light energy use have been neglected in most cases. According to the Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015 2015), artificial lighting and heating/cooling are considered major contributors to the energy consumption of public buildings in China.

The International Energy Agency has also indicated that in a typical office building, artificial lighting consumes the bulk of the energy, followed by cooling and heating operations (IEA 2014). Therefore, it is difficult to determine the real effect of geometric factors on the total energy consumption without accurate calculation of the lighting energy.

Furthermore, relatively rough building models are being constructed in the current research. It is hard to predict the energy performance of a whole building if only one single office room unit is being constructed in the prototype model (Shen and Tzempelikos 2013; Susorova et al. 2013). In addition, the differences between functional and auxiliary areas are ignored in most cases. Some of the geometry departs from real practice (Ourghi et al. 2007; AlAnzi et al. 2009). The large amount of internal heat gains from heat sources and particular occupancy patterns are sometimes neglected (Aksoy and Inalli 2006). To this end, more in-depth studies featuring an architectural point of view and global energy use data in this field should be conducted.

The aim of this study is to investigate the impact of building geometry design parameters on building energy performance, with particular consideration of lighting demand integrated with available instantaneous daylight for each daylight zone, taking high-rise office towers in Tianjin as an example. A prototypical office building model is created based on survey data, and annual heating, cooling, lighting and total energy consumption are simulated for each parameter and later compared to analyze their energy-saving potential. Additionally, multi-parameter research is performed to determine the correlations between three key related parameters and energy consumption for a standard rectangle-shaped plane utilizing an exhaustive method. The considered factors of orientation, plane shape, floor area, plane shape factor, floor height, floor number, and window-to-wall ratio of each facade are insufficient to form the full list of geometric factors, however, they are known to be closely related to visual design and normally designed by architects in the early design stages. Also, they form the least required parameters to describe a high-rise office tower's basic morphological feature, ranging from site orientation, building plane configuration, elevation to fenestration. This study fills a current research gap, helping architects understand the effect of various geometry design parameters on the energy consumption of high-rise office towers, and leading them towards good passive design schemes.

The paper is organized in the following way. In Section 2, the detailed simulation tool is first described, a prototype office tower model is established based on the survey data, and the geometry design parameters to be evaluated are discussed. Section 3 displays and discusses the results of the single-parameter and multi-parameter research. Section 4 presents the conclusions and identifies issues for further research.

2. Study Approach and Development of Building Model

2.1 Simulation tool

Energy simulation software is an effective tool to study the energy performance of buildings, and DesignBuilder, DOE-2, EnergyPlus, TRNSYS, BLAST, DEST, PKPM are some such tools currently used. In this study, the annual energy consumption simulation is conducted using DesignBuilder (Version 4.3), energy analysis software using the EnergyPlus simulation engine (DesignBuilder n.d. 2016). The Energyplus daylighting model, in conjunction with thermal analysis, determines the energy impact of daylighting strategies based on an analysis of daylight availability. The DesignBuilder provides a user-friendly interface for the modeling and parameter setting procedure. When lighting control is switched on, one or two sensors are placed in each daylight zone, and daylight factors are calculated. The reduction in electric lighting depends on the level of daylight illuminance, the target illuminance value, the lighting control type and the fraction of the lighting units controlled. There are three lighting control types in DesignBuilder: continuous, continuous/off, and stepped control.

2.2 Prototypical office tower

A prototypical office building model is created in DesignBuilder. The defining characteristics are based on a survey of 50 actual projects built between 2000 and 2015 in the cold zone of China. This paper focuses on high-rise office buildings with building heights between 24 m and 100 m. According to the survey, the geometry design parameters of high-rise office towers located in the cold zone of China are summarized in Table 1. Building orientation is affected by the urban road layout, with south being a common orientation of the main facade. The floor area commonly applied is in the range of 1000-2000 m^2, with square- or rectangular- plane geometry. Floor-floor height is in the range of 3.6-4.8 m by module of 0.3 m. Windows are typically equally distributed on all sides, with the window-to-wall ratio varying from 0.3 to 0.7. The number of floors is scattered between 8 and 24.

Based on the survey, the floor area of the prototypical model is assumed to be 1444 m^2. The model has a square-shaped plane with both the plane length and width being 38 m. The four facades of the building face the N, S, E and W orientations. The model is located in a stand-alone site with no surrounding buildings. The floor-floor height is set to 4.2 m. The fenestration of each façade is kept the same with horizontal windows and a window-to-wall ratio of 0.5. No shading devices are considered in the model. The building model is assumed to have 18 floors. The building has a total floor area of 25,992 m^2 (1444 m^2/floor), and a total height is 75.6 m (4.2 m/floor). Each floor in the model is divided into four air-conditioned zones and one core zone. The office area is set to 80% of the total floor area, as obtained from the survey. The core was assumed to comprise stairs, elevators and common spaces (e.g., hallways, tube well and equipment room). The plane, section and elevation of the prototypical model are shown in Fig. 1.

Each office space is assumed to have one lighting control sensor placed at the border of the defined daylighting zone. To locate the lighting control sensor, a southern-oriented office zone is taken as an example to perform daylighting analysis. The surface properties are set according to the lighting standard (GB 50034-2013 2013). The DaylightFactor (DF) is calculated and shown in Fig. 2. In particular, DF gives the percentage of the illuminance due to daylight on the indoor working plane (lux) to simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (lux). Accepted values for DF should be higher than 2% for office spaces (JGJ 67-2006 2006). As illustrated in Fig. 2, the sensor is placed 7.5 m away from the perimeter wall in the middle of that line at a height of 0.8 m (working plane height). The percent of artificial lighting units controlled by the sensor is 80%, equal to the ratio of daylighting zone area to office zone area. The lighting control type is continuous control on the assumption that the electric lighting units will be always on for deeper areas in working hours. No sensors are used to control the artificial lighting in the core zone because it is assumed daylighting is unavailable in that zone.

In most cases, fabric materials, building system and occupancy are still unclear during early design stages. So they are specified using default values. As shown in Table 2, the thermal properties of the model's envelope are defined by the minimum requirements set by Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015 2015). The component composition is representative of that used in the investigated cases. Assumptions for the HAVC system, occupancy, lighting, and office equipment are listed in Table 3 (GB 50189-2015 2015; GB 50034-2013 2013). In this paper, the HVAC emitters are fan coils for both heating and cooling. Taking into account local practices in the cold zone of China, a gas boiler is used as a heating source, whereas electricity from the grid provides the energy for cooling. The mechanical ventilation rate is set according to the minimum requirements in energy efficient design standard with no heat recovery applied. The heating and cooling demand of the core zone is not considered, on the assumption that exhaust air from the office zone serves as fresh air of the core zone. Common office space occupancy patterns and schedules suitable for China are utilized, as shown in Fig. 3. During weekends, it is assumed that the lighting, equipment and cooling system in the office model will be off, and the heating system will work to meet the setback temperature. Taking Tianjin as a representative city of the cold zone of China, the heating period lasts from Nov 15th to Mar 15th of the next year, and the cooling period lasts from May 15th to Sep 15th.

All calculations are carried out for a one year period of time (8760 h) using the climatic data of Tianjin. The weather data are titled China standard weather data, measured by the China Meteorological Bureau and Tsinghua University (EnergyPlus n.d. 2016). As shown in Fig. 4, the trends for hourly mean temperature and total horizontal solar radiation are similar, both fitted smoothly to a curve. In winter, the temperature goes below 5° C most frequently, and the extreme temperature drops to as low as -13.9° C. The temperature difference between indoor and outdoor leads to potential large heating losses, which result in high heating demand in winter. In summer, the temperature exceeds 25° C most of the time, and the extreme temperature goes up to 36.9° C; so there is cooling demand in summer. Spring and autumn are comfortable and relatively short, with temperatures between 10° C and 20° C.

Based on the simulation conditions described above, the heating and cooling demand, and the lighting energy use of the prototypical model are simulated, and the defined annual total end-use energy consumption (an adding up of the three parts) is calculated using the following equation (1). Office equipment energy consumption is not included in total energy because it is unlikely to be affected by geometric design parameters. In China, energy consumption of public buildings in the cold zone is generally classified into two categories, energy consumed for heating and energy consumed for other than heating (THUBERC 2016), the former is mainly from a district heating or boiler (coal/gas), and the latter is largely from grid. An electricity equivalent approach is utilized to convert building energy use data, because for office buildings, electric energy has the highest rate of consumption. The resulting data on building energy uses are calculated based on the following equations (2-3) (GB 50189-2015 2015).

(1)

where E_T = annual total end-use energy consumption (kWh/m^2.yr), E_H = annual heating energy consumption (kWh/m^2.yr), E_C = annual cooling energy consumption (kWh/m^2.yr), and E_L = annual lighting energy consumption (kWh/m^2.yr).

(2)

where Q_H = annual heating demand (kWh/yr), A = total building area (m^2), cop_H = the comprehensive efficiency of the gas boiler heating system, set as 0.8, q_1 = calorific value of standard natural gas, set as 9.87 kWh/m^3, q_2 = standard coal consumption for power generation, set as 0.36 kgce/kWh, and φ = conversion factor between standard coal and natural gas, set as 1.21 kgce/ m^3.

(3)

where Q_C = annual cooling demand (kWh/yr) and cop_c = the comprehensive efficiency of the cooling system, set as 2.5.

The results shown in Fig. 5 compare the energy use of prototypical model with or without lighting control device, and thus reconfirm the necessity of conducting such research on building energy consumption considering daylight integration. This finding indicates an increase of heating energy consumption and a decrease of cooling energy consumption as a result of the reduced lighting energy use with lighting control device. It can be inferred from Fig. 5 that lighting control is able to reduce the annual lighting energy consumption and total energy consumption by 56.2% and 24.6%, respectively.

The prototypical model is verified by analyzing the monthly distribution of building energy consumption, and examining the indoor air temperature of the office zone in selected winter and summer weeks. As shown in Fig. 6, there is a strong correlation between heating/cooling energy consumption and season changes, whereas lighting energy shows small variation. The prototypical model consumes 33.90 kWh per square meter per year, with heating, cooling, and lighting accounts for 36.1%, 39.5%, and 24.3%, respectively. Total electricity consumption amounts to 21.64 kWh per square meter per year, slightly lower than the average value of commercial office buildings in Tianjin, which is 40-100 kWh/m^2.yr (THUBERC 2014). The interval is explainable taken into account two aspects: firstly, the prototype model is equipped with lighting control devices, resulting in electricity energy reduction; secondly, office equipment energy consumption is excluded from current research. According to Fig. 7, indoor air temperatures of the office zone reach the setting temperature in selected winter and summer weeks, with no overheating or overcooling occurring. The selected winter week is 9th Jan to 15th Jan, and the selected summer week is 17th Jul to 23rd Jul. Therefore, the output energy consumption data of the prototypical model are reasonable, and the model can be used for further research.

2.3 Geometry design parameters

Geometry design considered during the early architectural design process, include orientation, plane shape, floor area, plane shape factor, floor height, number of floors and window-to-wall ratio. Table 4 lists the parameters that have been considered in the paper. The development of comparative geometry parameters are based on the survey in Section 2.2. Six orientations are tested, ranging from 15 degrees to 75 degrees south by east. Five plane shapes have been tested, including a square -shape, triangle -shape, cross -shape, circle -shape and oval –shape, which accounts for 72%, 2%, 6%, 2%, 4% of the total investigated cases, respectively. Five floor areas have been tested: 1024 m^2, 1225 m^2, 1444 m^2, 1764 m^2, and 2025 m^2. As to the rectangle-shaped plane, plane shape factors of 1/2, 1/1.5, 1/1, 1.5/1, and 2/1 have been evaluated. Based on practice, when a square -shape plane is elongated, the core zone is also elongated for the purposes of convenient use and evacuation. Therefore, different plane layouts have been set for plane shape factors of 1/2, 1/1.5, 1.5/1, and 2/1. Five floor heights, 3.6 m, 3.9 m, 4.2 m, 4.5 m, and 4.8 m have been evaluated. Floor numbers of 8, 12, 18 and 24 have been tested, with the same floor height of 4.2 m. In addition, window-to-wall ratios of 0.3, 0.4, 0.5, 0.6, and 0.7 have been evaluated, keeping a constant floor height of 4.2 m and sill height of 0.8 m.

3. Results and Discussion

3.1 Single-parameter research

In this sector, geometry design parameters are evaluated separately for the prototypical model. During the examination of a specific parameter, all the other parameters maintain the default values. This section uses whole building models. The energy saving rate is employed to assess the energy performance of individual cases when compared with that of the prototypical model, which means the prototypical model is used as a base case here.

3.1.1 Orientation

In terms of orientation, the results show that all orientations except O1 (typical orientation) will lead to a rise in total energy consumption. From Fig. 8, it can also be interpreted that for cases other than O1, heating and cooling energy consumption slightly increases, whereas lighting energy consumption remains constant, in comparison to those of the typical case.

3.1.2 Plane shape

The results in Fig. 9 show that a triangle-shaped plane, cross-shaped plane and oval-shaped plane can reduce the total energy consumption by 0.8%, 1.4% and 4.0%, respectively. For the triangle- and cross-shaped plane, it can be interpreted that the daylight conditions are improved and consequently lighting energy consumption is reduced, while heating energy consumption slightly increases. As regards to the oval-shaped plane, functional plane depth is reduced and lighting energy decreases. Also, cooling energy is reduced because negative orientations such as west and east are avoided. By contrast, the daylight conditions of the circle-shaped plane are weakened, resulting in significantly more lighting energy consumption and a negative energy saving rate, although heating energy is slightly reduced.

3.1.3 Floor area

As shown in Fig. 10, floor areas of 1024 m^2 and 1225 m^2 achieve energy saving rates of 0.7% and 0.5%, respectively. Floor area is correlated with the functional plane depth, and consequently the distribution of daylight throughout the daylight zone. As to the square-shaped plane, when the floor area is increased, the functional plane depth increases accordingly, and the available daylight per unit area could be reduced, resulting in more lighting energy consumption. The total energy consumption increases when the increase in lighting energy consumption exceeds the reduction in heating and cooling energy consumption, as is the case with floor areas of 1764 m^2 and 2025 m^2.

3.1.4 Plane shape factor

According to the simulation results shown in Fig. 11, elongated plane shapes with plane shape factors of 1.5/1 and 2/1 achieve energy saving rates of 1.2% and 3.1%, respectively. When the plane shape factor increases from 1/2 to 2/1, lighting energy consumption increases first and then decreases; however, heating and cooling energy consumption is reduced consciously, which is mainly explained by the fact that a longer façade profits of best orientation (South). Total energy consumption remains constant when the plane shape factor increases from 1/2 to 1/1.5, and subsequently decreases when the plane shape factor increases from 1/1.5 to 2/1.

3.1.5 Floor height

Floor-floor height is neglected in most previous studies focusing on the effect of geometry parameters on building energy performance. However, when taking daylight into consideration, floor height affects the air-conditioned volume and the daylight condition, which may have adverse effects on building energy performance. As shown in Fig. 12, floor heights of 3.6 m and 3.9 m achieve energy saving rates of 4.5% and 2%, respectively. Increases in heating and cooling energy consumption, particularly heating energy consumption, are observed with increasing floor heights due to the resulting increase in the volume of unit area to be heated and cooled, which greatly exceeds the slight reduction in lighting energy. Therefore, the total energy consumption increases significantly as the floor height increases.

3.1.6 Floor number

From the results shown in Fig. 13, it can be concluded that floor number affects the total normalized energy consumption only marginally. A floor number of 24 achieves an energy saving rate of 0.2%, because lighting energy is slightly reduced, while heating and cooling energy remain constant, in comparison to those of the typical case.

3.1.7 Window-to-wall ratio

Window-to-wall ratios of 0.3, 0.4, 0.5, 0.6, and 0.7 have been tested for each side of the prototypical model, and the results are shown in Fig. 14. Although windows are typically equally distributed on all sides in local high-rise office building practices, it is still advisable for architects to lower the window-to-wall ratios of the east, west, and north for energy conservation. Based on Fig. 14, a large increase in heating and cooling energy consumption and a slight decrease in lighting energy consumption are observed with increasing window-to-wall ratios to the east, west, and north. Regarding the southern facade, the reduction in heating and lighting energy consumption is compensated by an increase in cooling energy consumption as the window-to-wall ratio increases. Hence, architects can choose any window-to-wall ratio for the southern façade.

This section presents a sensitivity analysis of seven building geometric design parameters. The purpose is to identify the more important factors with respect to building energy performance so as to simplify further study in the next step. A slight variation in the total energy consumption with orientation alteration is observed. The effect of plane shape on energy performance is studied. Triangle -shapes, cross -shapes and oval -shapes improve the building energy performance mainly by reducing lighting energy consumption. The correlations between energy consumption and floor area, plane shape factor, and floor height turn out to be relevant, and these effects are further investigated in Section 3.2. Floor number has less of an impact on total energy consumption compared with the other parameters. In addition, smaller window-to-wall ratios to the east, west, and north are recommended for the prototypical model for the purpose of energy conservation.

3.2 Multi-parameter research

As mentioned in the survey of Section 2.2, a rectangle-shaped plane is commonly used in high-rise office tower practice in the cold zone of China. To correlate the three key geometric factors obtained from Section 3.1 (floor area, plane shape factor, and floor height) with the energy consumption for a rectangle-shaped plane, an intermediate story of the prototypical model is taken into consideration, and a total of 75 energy simulation cases are run in regards to 3 floor areas (1024 m^2, 1444 m^2, and 2025 m^2), 5 plane shape factors (2/1, 1.5/1, 1/1, 1/1.5, and 1/2), and 5 floor heights (3.6 m, 3.9 m, 4.2 m, 4.5 m, and 4.8 m). Three story models are constructed for all the models in this section, with the upper and lower stories set as adiabatic blocks because no heat is assumed to be transferred through interior floors. The simulation results are presented and discussed in this section.

3.2.1 Optimal energetic solution

According to the research, the best combination of the 3 parameters yielding the lowest energy consumption for a standard rectangle-shaped plane has been identified. It is characterized by a total energy consumption of 30.64 kWh per square meter per year, a floor area of 1024 m^2, a plane shape factor of 2/1 and a floor height of 3.6 m. The optimal solution can produce building forms that are more energy efficient than all other considered forms.

There are also limitations to the optimal solution, because in real -life situations architects face many social, economic, environmental, technical and aesthetic constraints, and the form of the building has to respond to other forces. Therefore, the effects of separate geometric factor on building energy performance are analyzed in sections 3.2.2-3.2.4. The optimal solution will serve as a baseline, which means the energy saving rate of each case is calculated by comparing its energy consumption with that of the optimal model. According to Table 5, differences in the energy saving rate across the considered models can be up to 18.9%.

3.2.2 Floor area

According to Fig. 15, for most cases, when the floor area is increased, the lighting energy consumption increases due to reduced daylight per unit functional area, whereas the heating and cooling energy consumption decreases due to reduced exposed surface area per unit floor area. The increased lighting energy consumption is slightly higher than the decreased heating and cooling energy consumption in most cases. Consequently, the results indicate slightly increased total energy consumption with increasing floor area. The increment is not significant in any of the simulations, especially in the case of a plane shape factor of 1/2 and floor height of 4.8 m. The energy saving rates between cases having floor areas of 1024 m^2 and 2025 m^2 vary from -0.3% to 3.2%, as shown in Fig. 16. The effect of floor area varies with different plane shape factors and floor heights, and the variation in total energy consumption is more pronounced for the cases with a high -plane shape factor and, low -floor height. Hence, the effect of floor area on the total energy consumption is not always significant, but a slightly reduced energy consumption can be expected when it is designed properly.

3.2.3 Plane shape factor

As shown in Fig. 17, an increase in the plane shape factor can contribute to decreased heating and cooling energy consumption, whereas lighting energy consumption first increases and later decreases, due to variation of the functional depth. In total, the annual energy consumption decreases as a result of the increasing plane shape factor. The reduction is obvious, when comparing the energy saving rates of cases with a plane shape factor of 1/2 and those with a plane shape factor of 2/1, as shown in Fig. 18. The energy saving rates between cases having plane shape factor of 1/2 and 2/1 vary from 4.1% to 6.7%, depending on the floor area and floor height. The smaller the floor area, and the higher the floor height, the larger the energy saving rate variation is. Above all, a larger plane shape factor can be used to enhance energy conservation.

3.2.4 Floor height

Figure 19 compares the simulation results in regards to the floor height. A relatively large increase in heating and cooling energy consumption is observed with increasing floor height, which exceeds the slight decrease in lighting energy; thus, the total energy consumption increases significantly. The impact of the floor height also varies with the floor area and plane shape factor. For example, the larger the floor area and the larger the plane shape factor, the smaller the gradient of variation of total energy consumption is. The energy saving rates between cases with floor heights of 3.6 m and 4.8 m vary from 10.4% to 13.5%, as demonstrated in Fig. 20. Hence, energy savings can be achieved by reducing the floor height for all the considered cases.

4. Conclusions

In the present study, the effect of building geometric design parameters on the energy performance of high-rise office towers in Tianjin is theoretically studied. Single-parameter and multi-parameter research is conducted, and the primary results are summarized as follows:

1) According to the examination of the single-parameter of the prototypical office model, the correlations between energy consumption and the floor area, plane shape factor (the ratio of the plane length to the plane width, only as regards to a

rectangle-shaped plane), and floor height are found to be significant.

2) In the second step, the intermediate story of the prototypical office model is taken into consideration, and multi-parameter research is conducted. It is determined that differences in the building shape can lead to significant differences in total energy consumption. An optimal approach that minimizes the sum of energy use for heating, cooling and lighting is presented, with a floor area of 1024 m^2, a plane shape factor of 2/1 and a floor height of 3.6 m. Differences in the energy saving rate across all the considered models can be up to 18.9 %, when compared with the optimal model. Energy savings can be achieved without a large increase in initial investment by designing the building with a smaller floor area, higher plane shape factor, and lower floor height.

3) Slightly reduced total energy consumption can be expected for the reduced floor area because daylight distribution of the office zone is improved and, consequently, the lighting energy consumption is reduced, exceeding the heating and cooling energy consumption increment. Increasing the plane shape factor improves the building thermal performance in regards to heating and cooling energy consumption, whereas lighting energy consumption first increases and then decreases. In total, the annual energy consumption decreases as a result of increasing the plane shape factor. Floor height reduction can be utilized to achieve a relatively high energy reduction, for a relatively large decrease in heating and cooling energy consumption is achieved, greatly exceeding the slight increase in

lighting energy.

4) This could have important application in three specific areas. First, architects aiming at an energy-efficient high-rise office tower design in Tianjin are provided with guidelines as regards to early design stage. It is envisaged that some principles are also applicable to similar climates. Second, current energy efficient design standard make use of shape coefficient to describe a building's thermal performance. It is necessary to note that the present study shows that conventional ways of thinking (e.g., preferable of a more compact shape in a cold climate) are not always true in regard to global considerations of heating, cooling and lighting energy use. Third, it is believed that the approach can be extended to other building types at different locations and with other simulation tools.

5) Limitations and future work. First, the interaction effects between geometric factors and fabric materials, building system and predicted occupancy parameters are not included in the present research. In case of parameters with large impacts, such as the comprehensive efficiency of the HVAC system, the definition of default value itself can significantly alter the conclusion. So, the outcome in this paper is only applicable under specific assumptions and thus should be treated with caution. Second, a prototypical high-rise office tower model is established in this paper based on survey results, which will serve as a start point for future research relate to more wider range of parameter sensitivities such as different

urban built environment and climate. In that case, parametric simulation tools will be needed in order to generate numerous potential combination results.

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Tables

Table 1 Geometry design parameters of high-rise office towers based on the survey.

Geometry design parameter	Range or typical value
Orientation	South
Floor area	1000-2000 m^2
Plane shape	Square- or rectangular- plane
Floor-floor height	3.6-4.8 m
Window-to-wall ratio	0.3-0.7
Floor number	8-24
Functional area ratio	0.8

Table 2 Layers and properties of the exterior wall, roof, ground floor, internal floor, and glazing.

Layers (from outermost to innermost)	Thermal properties

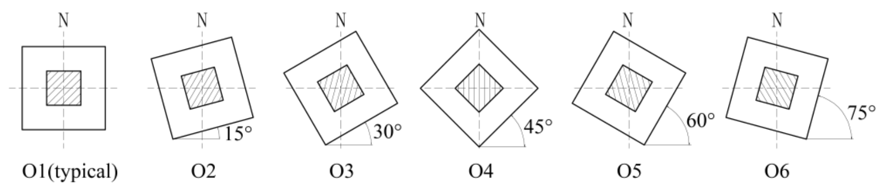
Exterior wall	Cladding (20 mm) Autoclaved aerated concrete blocks (300 mm, k= 0.16 W/m.K, ρ= 500 kg/m^3, C= 840 J/kg.K) Cladding (20 mm)	U-value= 0.5 W/m^2.K
Roof	Cladding (20 mm) XPS Extruded Polystyrene (70 mm, k= 0.034 W/m.K, ρ= 35 kg/m^3, C= 1400 J/kg.K) Reinforced concrete (100 mm) Cladding (20 mm)	U-value= 0.45 W/m^2.K
Ground floor	Foam (130 mm) Cast concrete (100 mm) Floor screed (70 mm) Flooring (30 mm)	U-value= 0.25 W/m^2.K
Internal floor	Cladding (20 mm) Cast concrete (100 mm)	U-value= 2.81 W/m^2.K
Glazing	Double pane, low-E (3/6/3 mm)	SHGC= 0.4 light transmission= 0.56 U-value= 2.2 W/m^2.K

Note: Air infiltration rate= 0.3 ac/h, air infiltration is assumed only for perimeter zones

Table 3 Assumptions for the HAVC system, occupancy, lighting, and office equipment.

HVAC system	Simple Fan-coil unit	
	Fuel	Heating from gas boiler, COP=0.8
		Cooling from grid, COP=2.5
	Set temperature	Heating: 20°C (Setback 5°C)
		Cooling: 26°C (Setback 28°C)
	Mechanical ventilation: 8.33 L/s. person (no heat recovery)	
	Natural ventilation: None	
Occupancy	Office: 1 person per 8 m^2	
	Core: 1 person per 50 m^2	
Lighting	LPD	9 W/m^2 for office
		3 W/m^2 for core
	Target illuminance	300 lux for office
Office equipment	13 W/m^2 for office	

Table 4 Geometry design parameters and schematic diagram of comparative models.

Orientation	

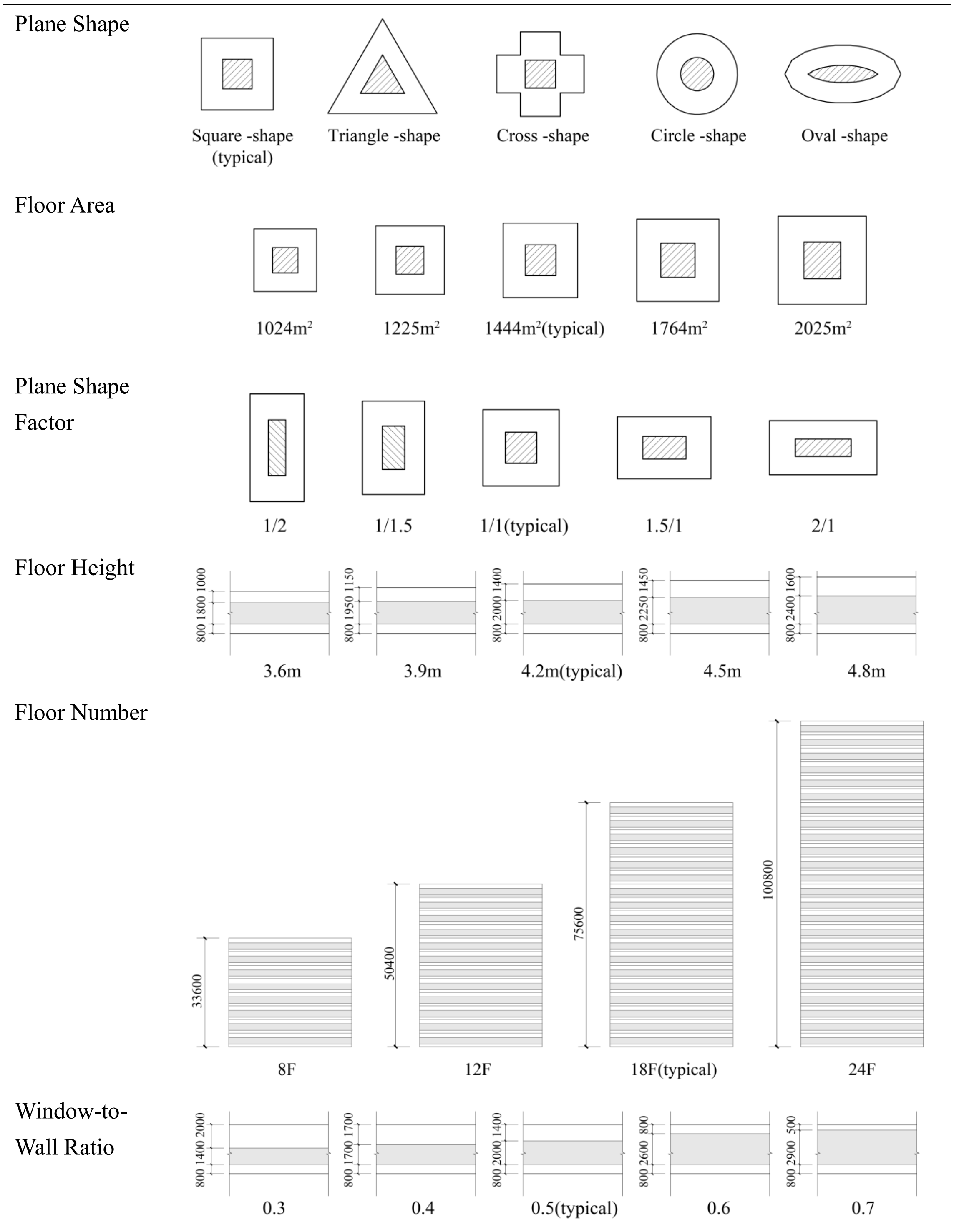


Table 5 Geometry design parameters and energy use data of the optimal and worst energy solution among the 75 simulation cases.

	Floor area (m^2)	Plane shape factor	Floor height (m)	Lighting ($kWh/m^2.yr$)	Heating ($kWh/m^2.yr$)	Cooling ($kWh/m^2.yr$)	Total ($kWh/m^2.yr$)	Energy saving rate (%)
Optimal	1024	2	3.6	5.90	11.44	13.29	30.64	0
Worst	1024	1/2	4.8	5.71	15.06	15.66	36.43	-18.9

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Figure Captions

Fig. 1 Plane, section and elevation of the prototypical model.

Fig. 2 DaylightFactor analysis of the southern-oriented office zone.

Fig. 3 Schedules for occupancy/lighting/equipment, heating, and cooling for weekday.

Fig. 4 Hourly mean temperature and solar radiation of Tianjin. The solar radiation is the sum of the diffusive and direct solar radiation on a horizontal plane.

Fig. 5 Energy comparison of the prototypical model with lighting control off/on.

Fig. 6 Monthly energy consumption of the prototypical model.

Fig. 7 Indoor air temperature of the office zone in selected winter and summer weeks.

Fig. 8 Energy performance of single-parameter comparative models: orientation

Fig. 9 Energy performance of single-parameter comparative models: plane shape

Fig. 10 Energy performance of single-parameter comparative models: floor area

Fig. 11 Energy performance of single-parameter comparative models: plane shape factor

Fig. 12 Energy performance of single-parameter comparative models: floor height

Fig. 13 Energy performance of single-parameter comparative models: floor number

Fig. 14 Energy performance of single-parameter comparative models: window-to-wall ratio

Fig. 15 Energy consumption versus floor area

Fig. 16 Energy saving rates between models having floor area of 1024 m^2 and 2025 m^2

Fig. 17 Energy consumption versus plane shape factor

Fig. 18 Energy saving rates between models having plane shape factor of 1/2 and 2/1

Fig. 19 Energy consumption versus floor height

Fig. 20 Energy saving rates between models having floor height of 3.6 m and 4.8 m

Figures

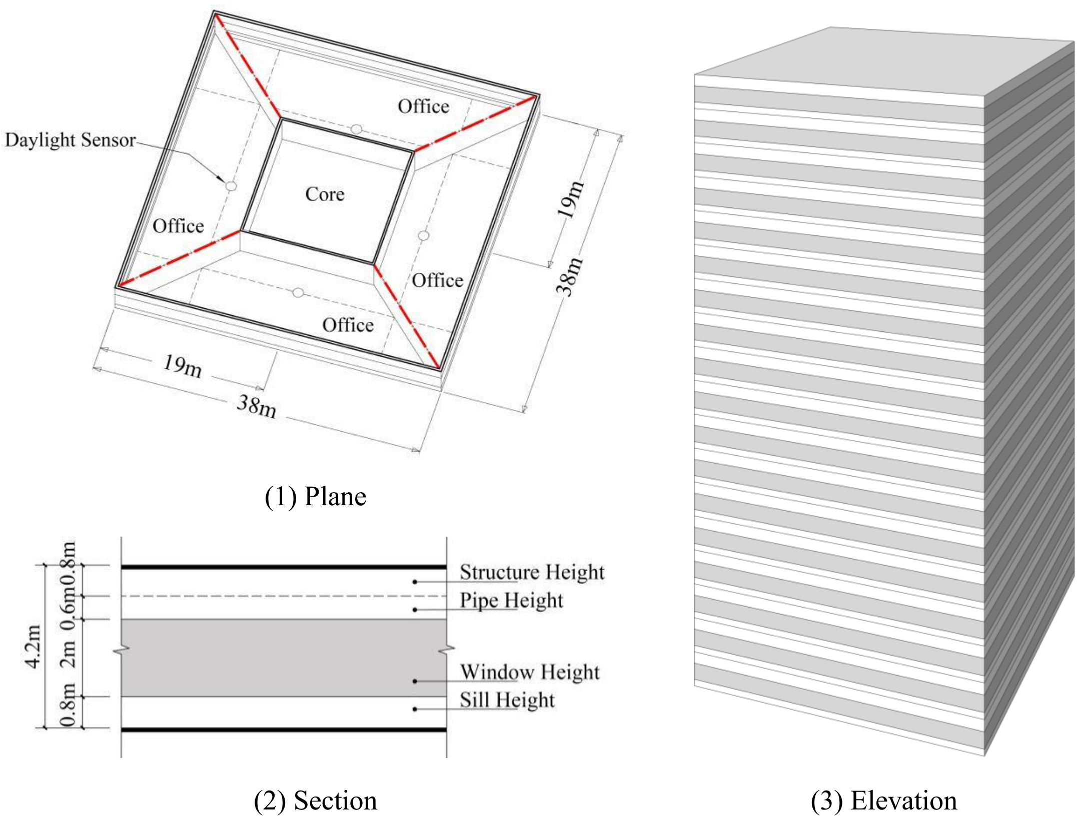


Fig. 1 Plane, section and elevation of the prototypical model.

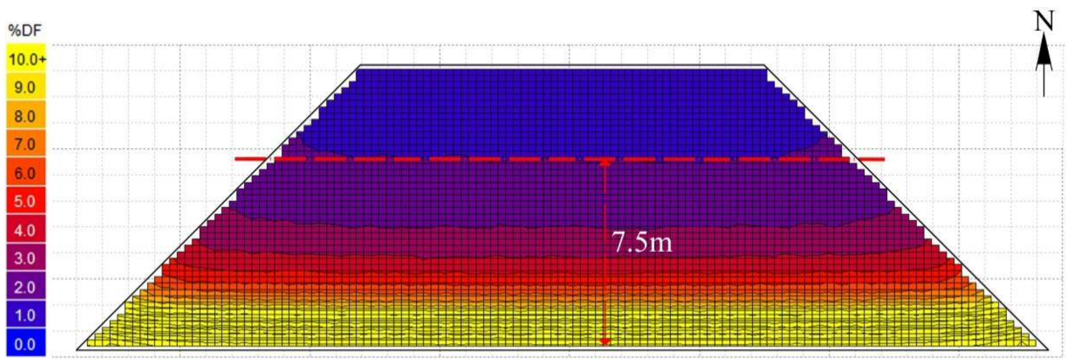


Fig. 2 DaylightFactor analysis of the southern-oriented office zone.

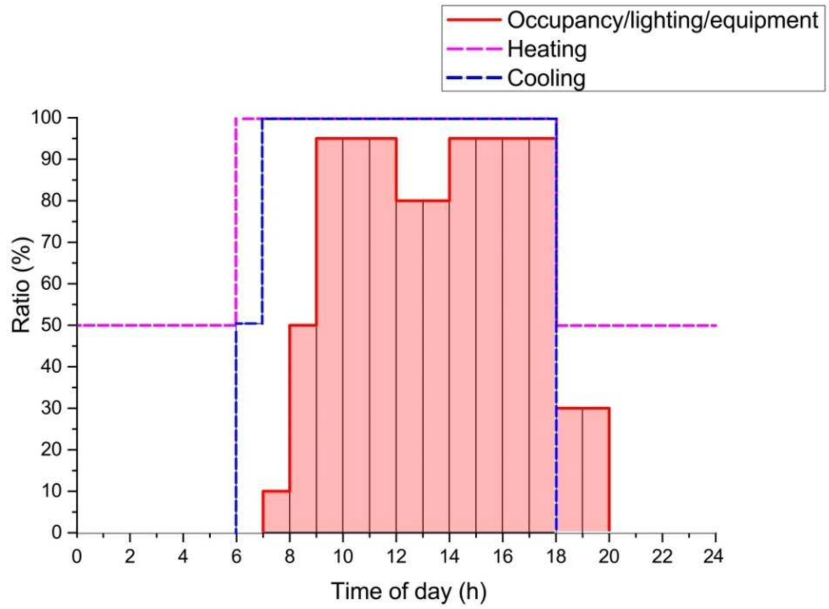


Fig. 3 Schedules for occupancy/lighting/equipment, heating, and cooling for weekday.

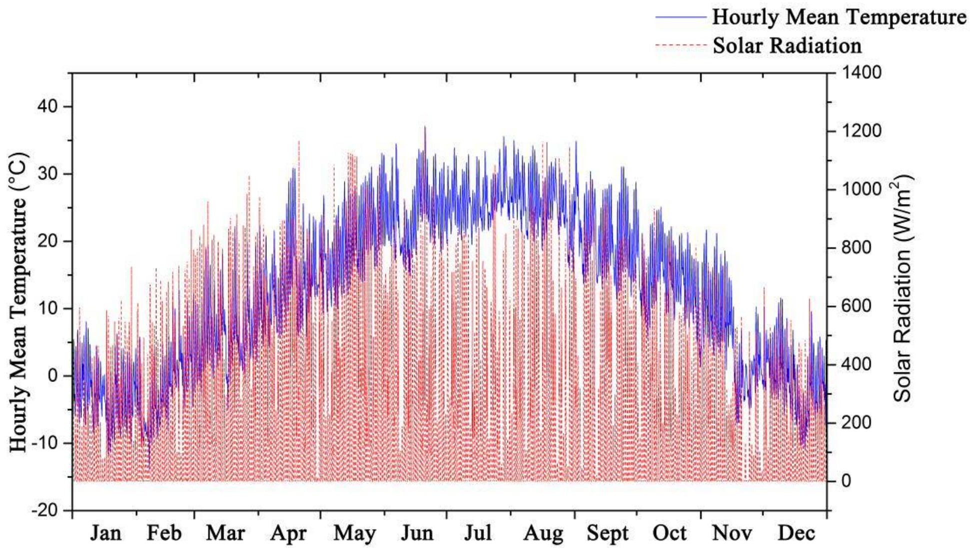


Fig. 4 Hourly mean temperature and solar radiation of Tianjin. The solar radiation is the sum of the diffusive and direct solar radiation on a horizontal plane.

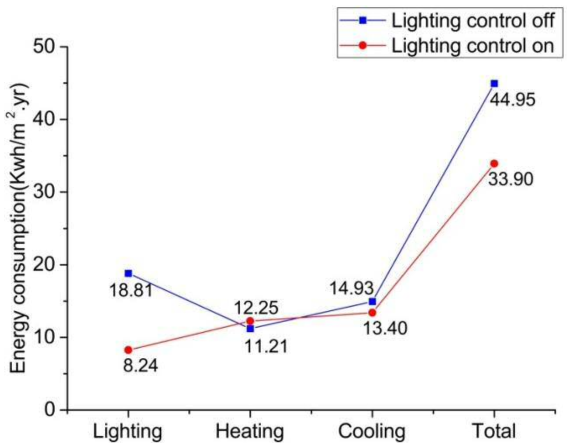


Fig. 5 Energy comparison of the prototypical model with lighting control off/on.

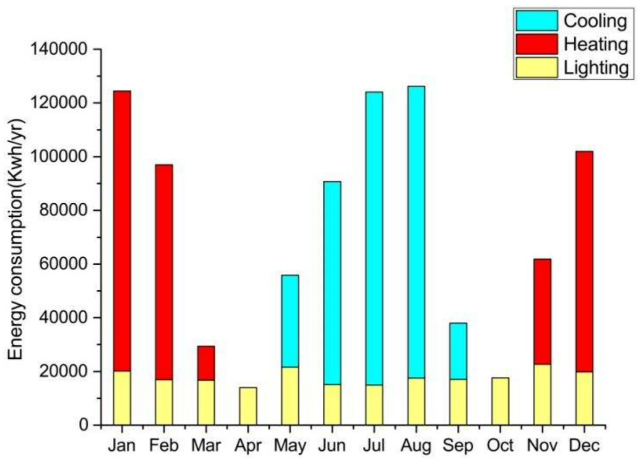
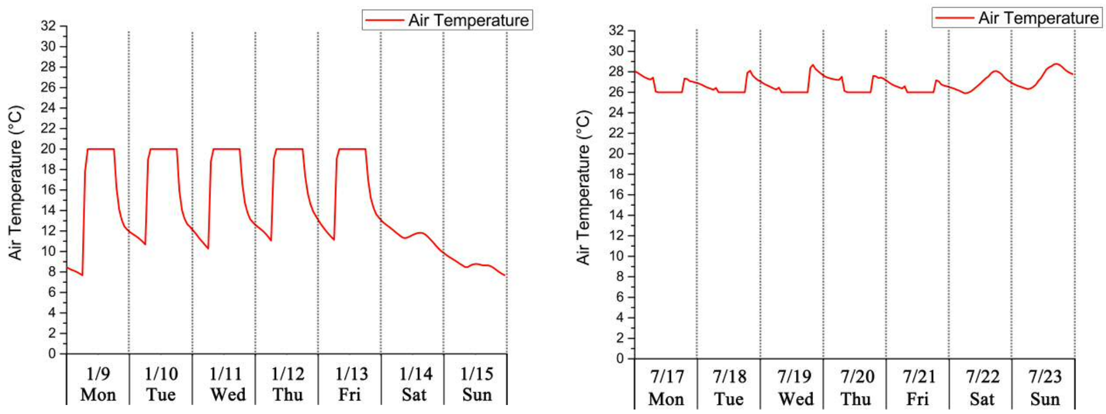
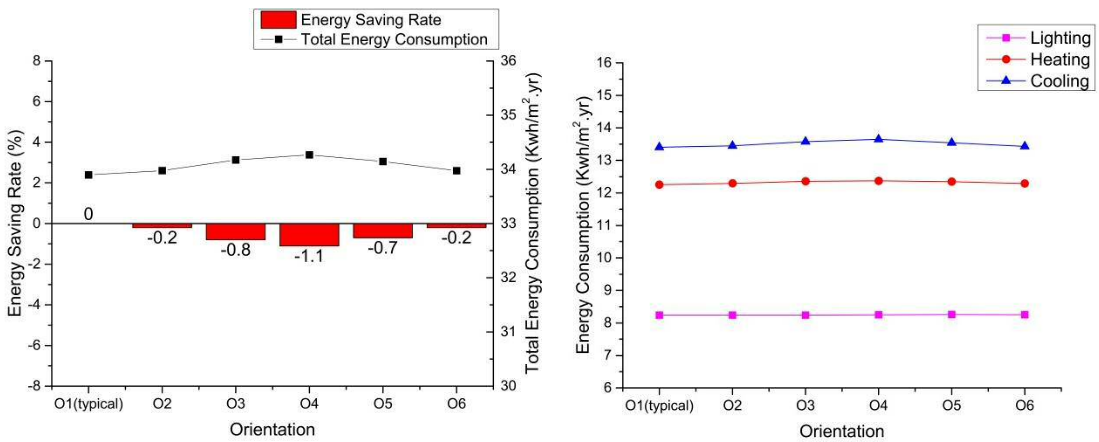


Fig. 6 Monthly energy consumption of the prototypical model.



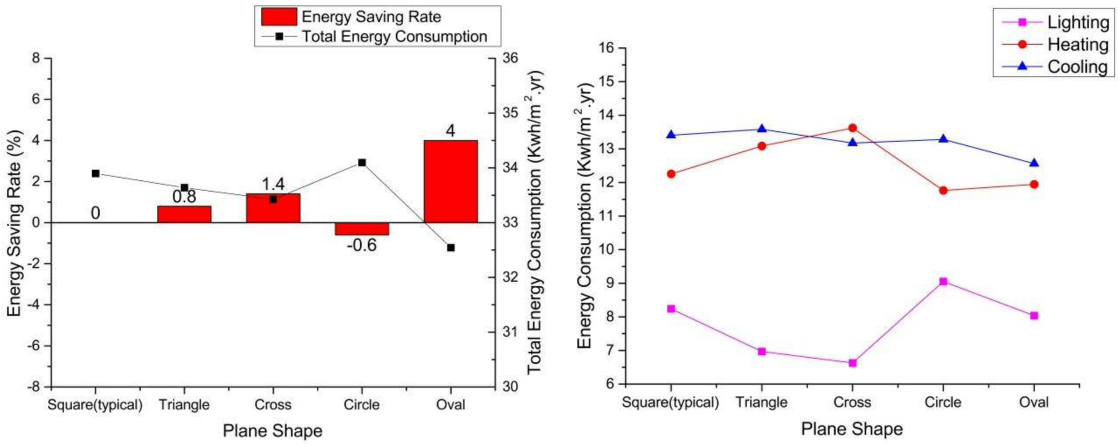
(1) Winter typical week (2) Summer typical week

Fig. 7 Indoor air temperature of the office zone in selected winter and summer weeks.



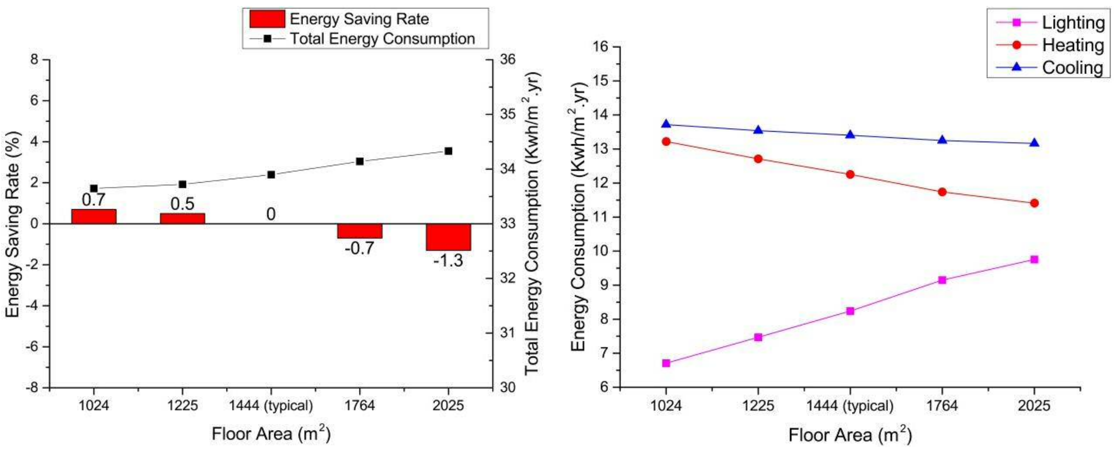
(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

Fig. 8 Energy performance of single-parameter comparative models: orientation



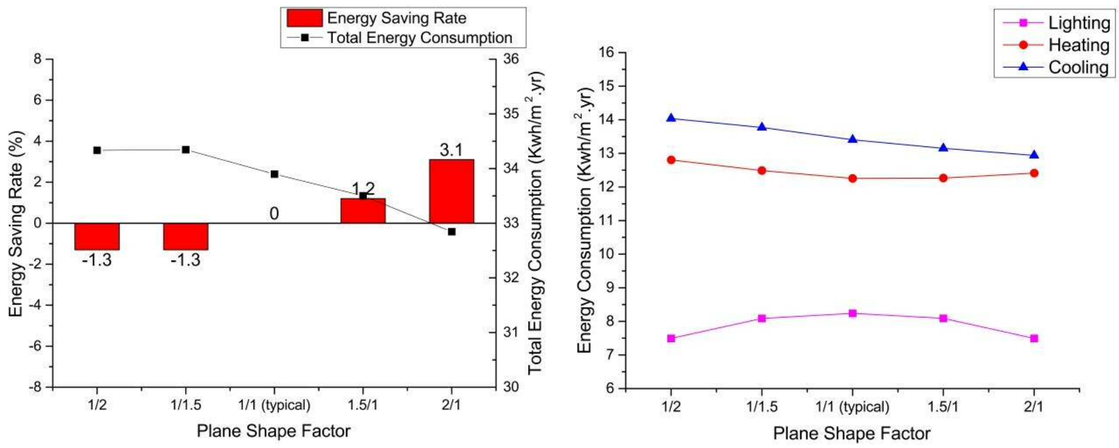
(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

Fig. 9 Energy performance of single-parameter comparative models: plane shape



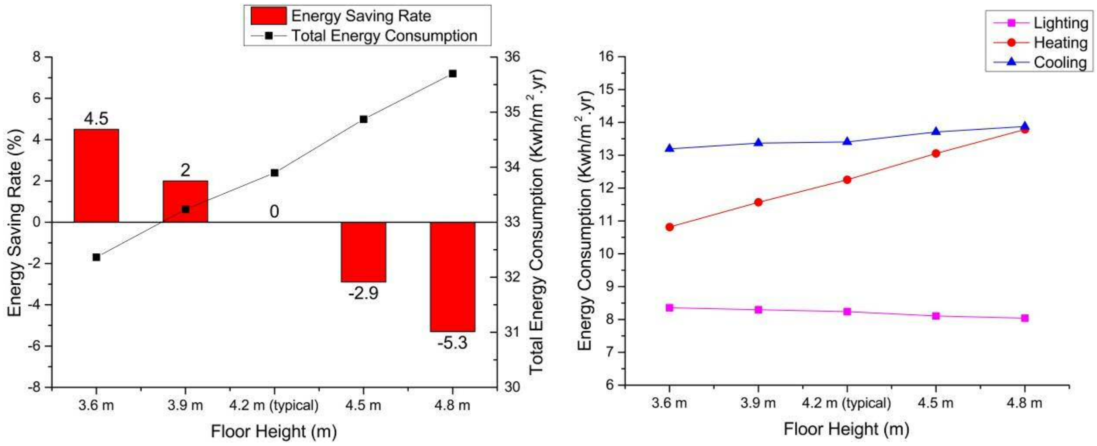
(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

Fig. 10 Energy performance of single-parameter comparative models: floor area



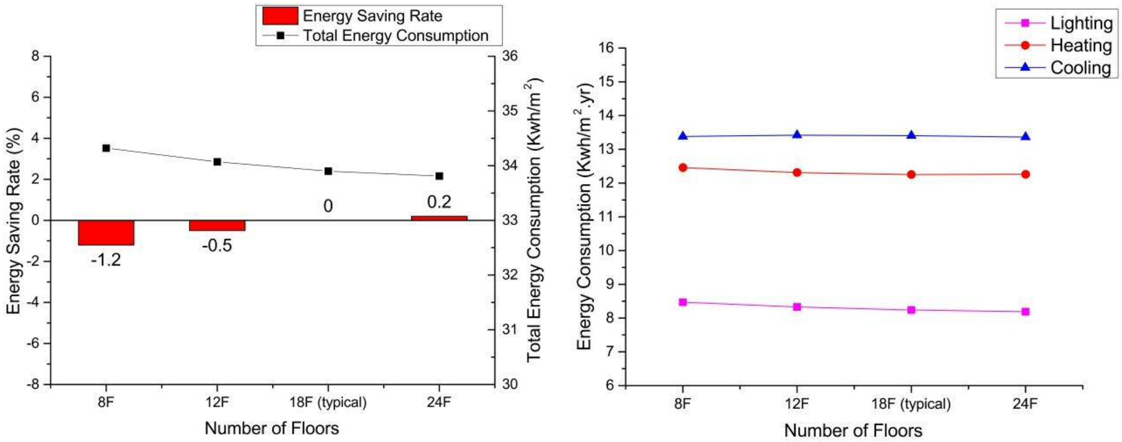
(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

Fig. 11 Energy performance of single-parameter comparative models: plane shape factor



(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

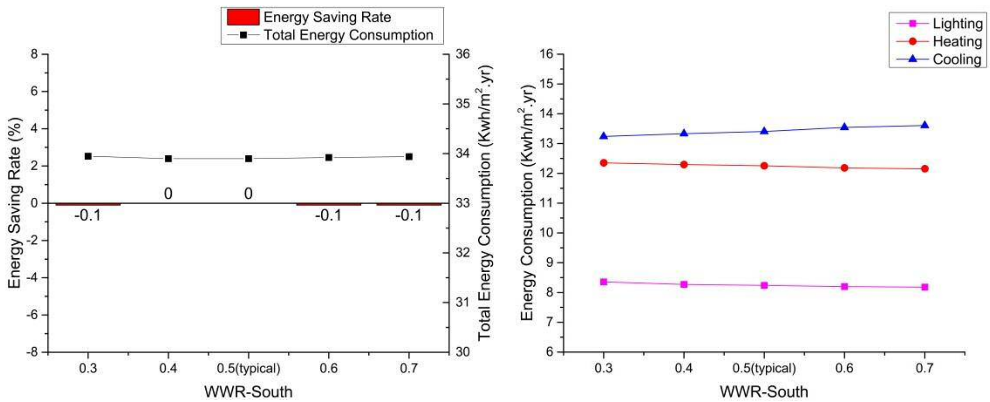
Fig. 12 Energy performance of single-parameter comparative models: floor height

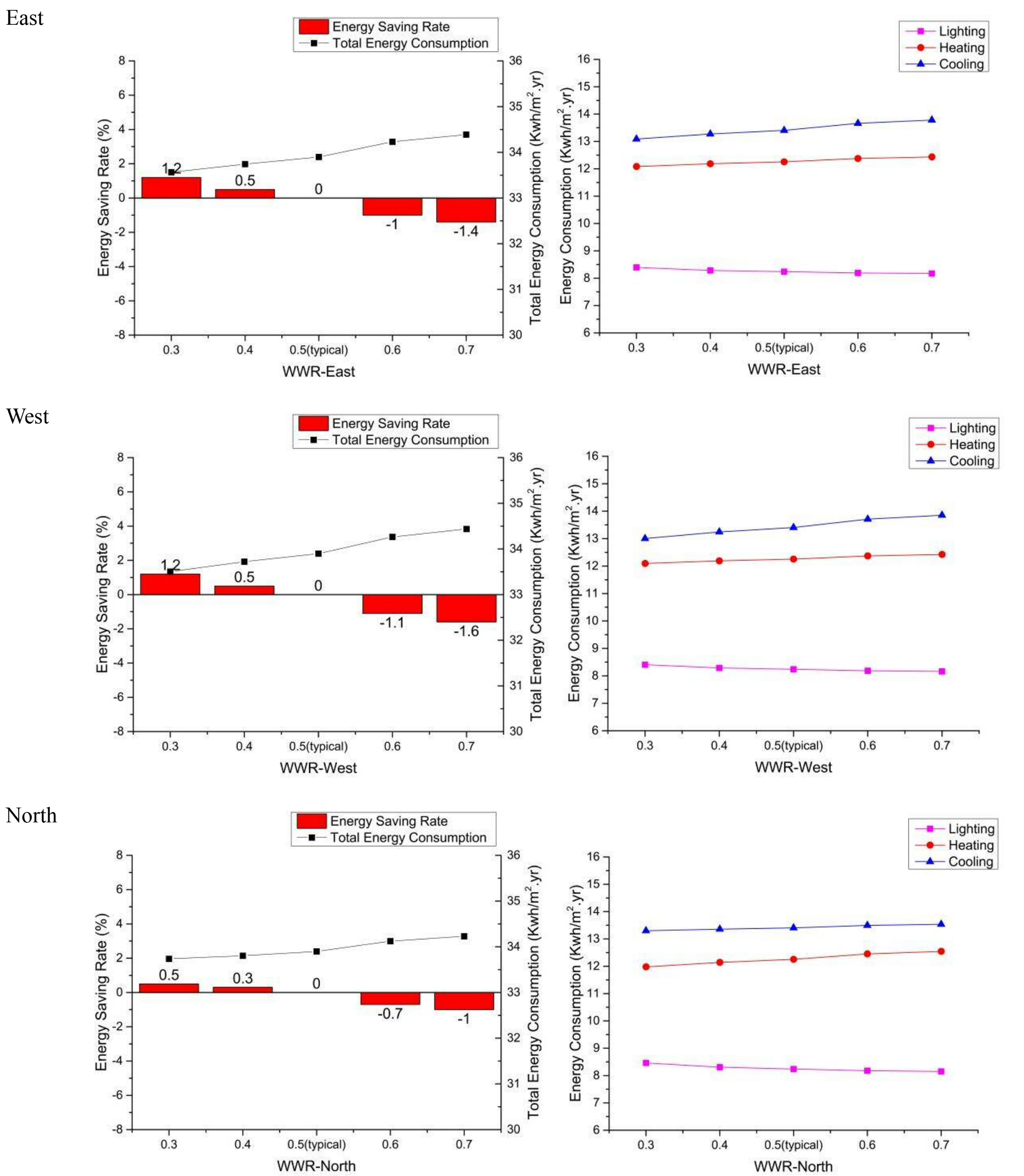


(1) Energy saving rate and total energy consumption (2) Lighting, heating and cooling energy consumption

Fig. 13 Energy performance of single-parameter comparative models: floor number

South





(1) Energy saving rate and total energy consumption

(2) Lighting, heating and cooling energy consumption

Fig. 14 Energy performance of single-parameter comparative models: window-to-wall ratio

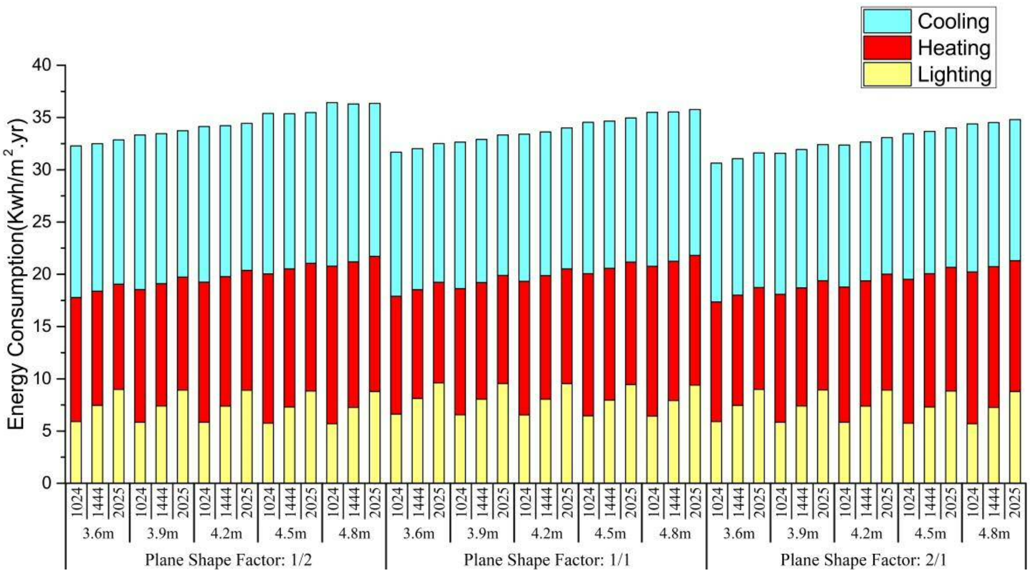


Fig. 15 Energy consumption versus floor area

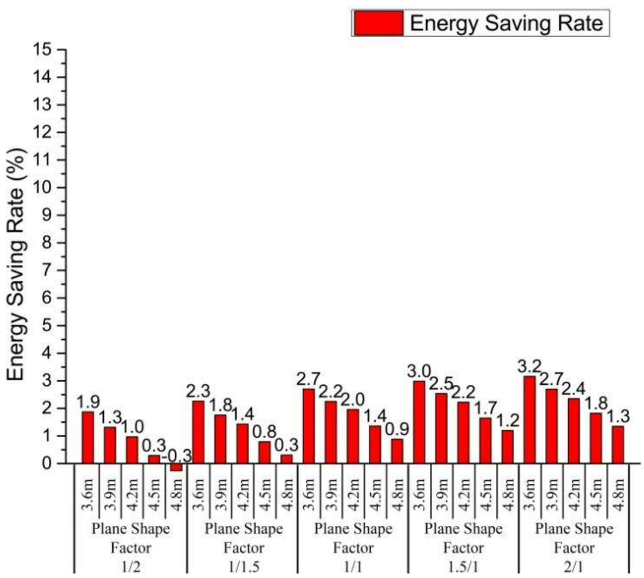


Fig. 16 Energy saving rates between models having floor area of 1024 m^2 and 2025 m^2

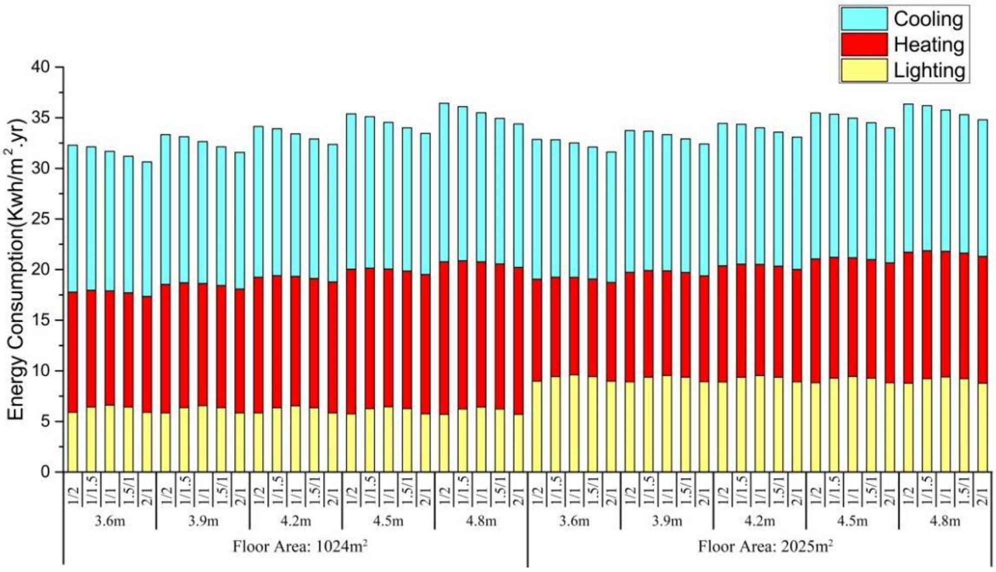


Fig. 17 Energy consumption versus plane shape factor

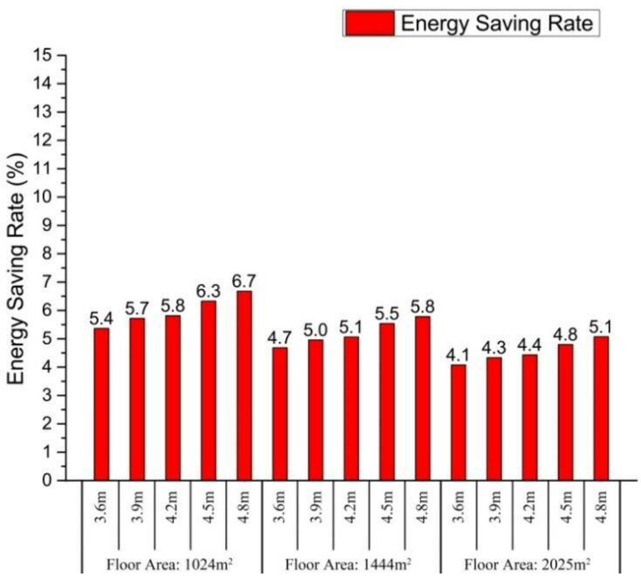


Fig. 18 Energy saving rates between models having plane shape factor of 1/2 and 2/1

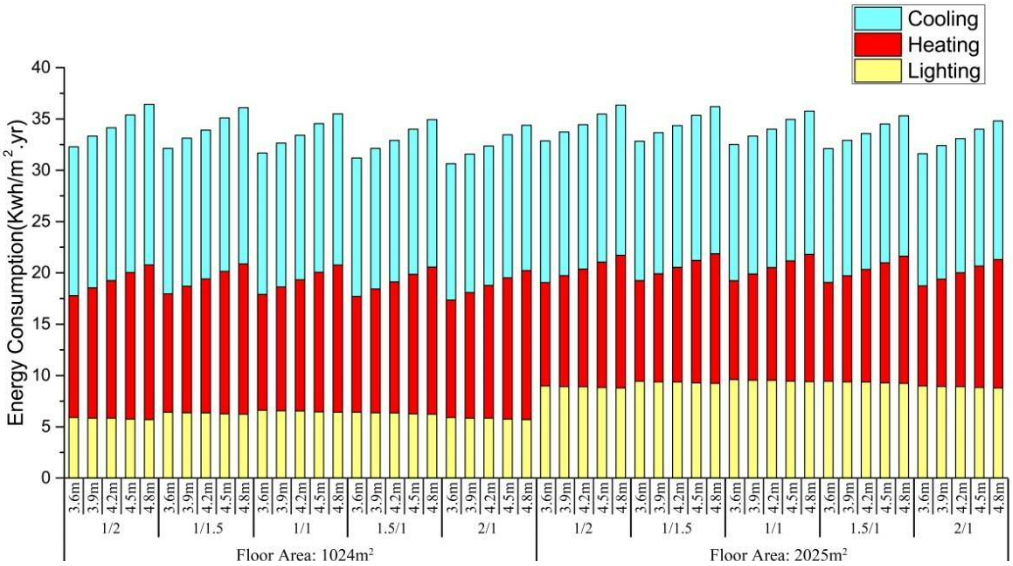


Fig. 19 Energy consumption versus floor height

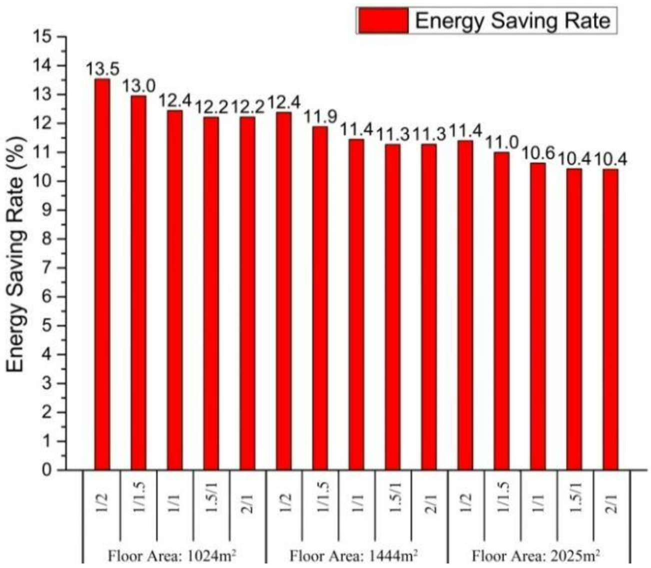


Fig. 20 Energy saving rates between models having floor height of 3.6 m and 4.8 m