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Manuscript title: Investigating the Influence of Neighbouring Structures on the Energy Performance of a High-Rise Residential Block

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Abstract

Urbanisation has increased rapidly in recent years, and more high-rise buildings are built to accommodate the increasing urban population. High-rise buildings affect solar conditions, which can have positive and negative effects on the surrounding areas. The present work evaluates how the building location and surrounding environment affects its energy performance by undertaking parametric modelling. In this research, a 12-storey residential building was investigated using a validated Building Energy Simulation (BES) model. The cities selected for this research are Copenhagen, Beijing and Singapore, which represents three different climatic conditions. The following parameters were discussed: surroundings quantity, position and height. In total, over 180 scenarios were modelled. The results showed that the surrounding buildings could positively and negatively influence the central building's performance. For a single building, the annual solar gain difference between Denmark and China was 46.2MWh, and the total energy load difference was 47MWh. The results indicate that the design is an important issue to consider for high-rise buildings as they can influence the energy use up to 10.17% when the central building was surrounded by eight double-height buildings with 15m spacing. The approach presented in this work can be used to inform early-stage design choices.

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Notation

c_p	Specific heat capacity
h_r	Surface heat transfer coefficient
K	Coefficient
$L_g(\beta)$	Long-wave radiation from the ground
$L_{skv}(\beta)$	Long-wave radiation received directly from the sky
M	Air mass flow rate
n	Coefficient
T	Temperature
T_a	Air temperature
T_{MRT}	Mean radiant temperature
T_i	Supply air temperature
T_s	Mean surface temperature
Q	Heat storage in air masses
V	Air volume
W	Heat flux vector
W_{hf}	Heat flux from the air to the surface
W_{rl}	Net radiative loss from the surface
β	External surface of inclination
ε_e	Emissivity of the exterior surface
λ	Conductivity

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$\boldsymbol{\Theta_e}$	Absolute temperature of the exterior surface
$\boldsymbol{\rho}$	Density
$\boldsymbol{\rho_a}$	Air density

1. Introduction

Urbanisation has increased rapidly in recent years. More high-rise buildings are built to accommodate the increasing urban population. Previous studies highlighted that increased urbanisation has led to urban areas having higher temperatures than rural areas, which also called the urban heat island (UHI) effect (Wong et al., 2011). Although cities take up about only 2% of the Earth land, they account for over 70% of the energy consumption (Nouvel et al., 2017). According to Lima et al. (2019), the energy consumption of buildings is growing rapidly, with the energy used by buildings in urban area accounts for over one-third of the total energy demand. Mardookhy et al. (2014) stated that 61% of the energy consumption of residential buildings is related to space heating or cooling. Tackling energy consumption is a crucial strategy for achieving carbon emission targets and sustainability. Many Asian countries such as Singapore and China led to the development of megacities with many high-rise residential buildings. Lam (1995) stated that in Hongkong, 90% of the population live in high-rise buildings, and about half of the buildings are densely built as public housing estates. The increasing requirement for thermal comfort has led to the heating and cooling of buildings becoming responsible for a significant portion of its total energy consumption (Vallati et al., 2015).

Hsieh et al. (2007) suggested that the ventilation, infiltration, heat from artificial lighting, solar irradiation through the fenestration and latent heat from moisture are the major influencing factors of the building heating and cooling loads. Nowadays, heating, ventilation and air conditioning (HVAC) systems are indispensable for providing comfortable indoor

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environments (Catalina, 2011, ASHRAE, 1992). It is verified that climate conditions affect building energy demands, indoor thermal conditions and comfort levels (Haase and Amato, 2009, Qi et al., 2014, Lam et al., 2008). Buildings which could not provide a comfortable indoor environment could lead to higher energy costs as people will manually adjust the set-points or use portable heating or cooling, which can cause additional energy demands. It is important to ensure the indoor environment is maintained at a comfortable level to minimise unnecessary or extra energy consumption. Yun (2018) stated that providing a comfortable environment for occupants is one of the key parameters to evaluate building performance.

Buildings with the height of 18m or over are defined as high-rise buildings (BREEAM, 2016). As the number of high-rise buildings is growing rapidly, the huge energy consumption of these buildings has become a public concern. Several studies mentioned that lots of factors might have impacts on high-rise buildings performance, such as ventilation (Prajongsan and Sharples, 2012), building geometry and layout (Liu et al., 2017), fabric materials (Granadeiro V, 2013), urban context (Samuelson et al., 2016), etc. Therefore, it is necessary to find the correlation between a building plane and its energy consumption during the design process. Raji et al. (2016) investigated the energy-saving solutions for envelope design of tall office building. Several factors which have impacts on high-rise building energy performance were analysed, which including glazing, window-to-wall ratio, shading, roof, insulation, air infiltration and operation schedule. Heating, cooling and lighting energy demands were analysed to show how each factor affects the building performance. A parametric study of a multi-storey wooden building showed that the optimisation of parameters can reduce 32% of

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annual energy consumption (Bruno et al., 2019). The work (Raji et al., 2016) concluded that solar radiation has a significant influence on building energy consumption, appropriate shadings could be necessary for saving cooling energy, 11.3% cooling energy can be saved with multiple strategies.

Although high building density could increase the urban temperature levels, high-rise buildings could also change wind environment and provide shadings for the surrounding buildings. Shen and Wang (2020) conducted a study on investigating how the wind environment affects the neighbourhood-scale building heating and cooling energy use per floor area in winter design conditions. According to the coupled BES and Computational Fluid Dynamics (CFD) simulation, the high-rise buildings could increase the wind speed and therefore, led to larger convective heat transfer coefficient (CHTC) value, and the CHTC can be greatly influenced when the neighbourhood form is changed. As high rise buildings are typically going to be surrounded by other high-rise buildings or structures, they can impose additional environmental factors such as reflections and shading from neighbouring buildings. These reflections and shading can create different microclimates from floor to floor and lead to different energy performance and thermal comfort. Wong et al. (2011) suggested that buildings surrounded by higher structures will have a lower temperature than other cases. The study highlighted that neighbouring or surrounding buildings could lower the shaded building's temperature during the hottest hour of the day.

According to a case study by Huo et al. (2020), the shading can help to maintain the indoor temperature of the shading zone lower than the zones without shading in summer. The

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aspect ratio (height-to-width ratio) H/W is typically used to define the geometry of a street canyon, where H is the buildings' average height and W is the distance between the opposite sides of the street canyon. It is suggested by Bourbia and Boucheriba (2010) that, for the street canyons with high aspect ratios, when the solar altitude angle is low in winter, the tall and narrow canyons restrict the solar radiation, which result in lower air temperature than in the canyons with low aspect ratios at daytime. At night, less radiative heat transfers to the sky in the deep canyons which cause higher air temperature than open spaces. However, the solar radiation can access the deep street canyons easier in summer than in winter because of the high solar altitude angle, which means the deep street canyons are less effective in blocking the direct solar radiation in summer (Emmanuel and Johansson, 2006). Estimating the heat gain from solar radiation is one of the most important parameters for researchers to analyse building envelopes and cooling load (Dutta et al., 2017). Therefore, the distance between adjacent buildings, building heights and density of buildings need to be considered when designing urban areas.

A study (Cheung et al., 2005) on high-rise apartment shows that the peak cooling load and energy consumption can be reduced by more than 15% by self-shading, which indicated that the effect by shadings could not be ignored. In high-rise building areas, shadings may cause by the other neighbouring high-rise buildings. Samuelson et al. (2016) investigated a case study residential high-rise building and found that the shading cast by neighbouring buildings can play an important part in the adjacent high-rise building energy performance. It shows that in New York, compared to the baseline condition, which there are no surrounding

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structures, the condition of low-density surrounding buildings decreased the annual cooling energy demand by 11% while the heating energy demand increased by 1%. Under the high-density generic urban context condition, the cooling energy demand decreased by 31% and heating energy increased by 8% (Samuelson et al., 2016). Shen and Wang (2020) researched on evaluating the impacts of three neighbourhood form control variables on the energy performance of the buildings in Chicago, a winter design day was selected for the simulations. The study showed that the neighbourhood form can influence on the CHTC value and external wall temperatures of both low-rise and high-rise buildings. It was also found that when the neighbourhood form changes, the high-rise buildings' energy uses were more sensitive to the outdoor environment. The effect of urban street morphology, especially the street canyons on the microclimates of cities has been investigated by many studies (Hondula et al., 2017, Erell, 2011).

Design parameters such as building shape, orientation and thermal mass can affect buildings; energy use. Besides those parameters, microclimate and the neighbourhood form are also the considerations for high-rise building design. It is suggested by Peeters et al. (2020) that appropriately designed shadings are helpful for mitigating the UHI phenomenon, and can also improve thermal comfort for pedestrians and affect people outdoor activities. The use of multi-parameter optimisation approach for the building design can achieve considerable energy savings and cost reduction while improving thermal comfort. To realise such potential, it is vital to examine the energy performance using building energy simulations (BES) tools. Ascione et al. (2020) stated that although the building energy consumption is highly affected by the inter-building effect (IBE), the increment of simulation times could be 46%. Ignoring IBE can simplify the model which requires lower computational complexity and time. The building energy optimisation algorithm can be speeded up with simplified and lighter models. Therefore, the energy-efficient, cost-effective and sustainable buildings can be developed by a wider domain of solutions. The structure of high-rise buildings is highly complex, and the buildings have higher performance requirements (Soebarto, 2011). These pose unique challenges to the energy simulation and optimisation of high-rise buildings.

Based on the review, a limited number of studies investigated the energy performance of high-rise residential buildings in different climate areas. There has been little focus on the influence of microclimate of building energy performance. The design variables such as window size, wall colour and insulations for improving thermal comfort and reducing energy consumption were discussed. In addition, most previous studies focused on how the UHI phenomenon affect the heating and cooling performance of buildings. There is little study on the association between building neighbouring structures and energy consumption. Furthermore, there is no parametric analysis of how the overall form of neighbouring buildings has an impact on high-rise building performance. The present work will address the gaps by evaluating the performance of a high-rise residential building which is surrounded by structures with different number and height. This paper aims to assess the energy and thermal performance of a 12-storey residential building by using Building Energy Simulation (BES). The building was located in three cities: Copenhagen – Denmark, Beijing – China and Singapore. The three locations with very different climate types allow comparing how the weather affects the building energy and thermal performance. One city was selected for comparing the impact of surrounding conditions, which included the surrounding buildings' height and density, and surroundings' position. The shading condition would change with the surrounding environment changing, which cause the energy consumption difference. In total, over 180 scenarios were modelled to understand the influence of the variation of different parameters.

2. Method

2.1 Building and Location

In this study, the model is based on a 12-storey residential building with an irregular shape, as shown in Figure 1. The height of each storey is 2.8m, and the total height of this building is 33.6m. Each floor has four flats, which contains bedrooms, living room, washroom and kitchen, while balconies are considered as outdoor. Public space includes corridors, stairs and lift, where no heating or cooling is provided.

The building construction and thermal properties were assigned for the different spaces (Table 1). For the case study building, we assumed a typical old construction building with insulated and thicker cavity walls and the U-values were set based on (Approved Document L1, 1991). The total number of building room spaces was 276. Corresponding thermal templates were assigned to each type of spaces (see Table 2), and each room was considered as a zone. To reduce the computational requirement and complexity, the BES geometry was simplified by excluding the terrace handrails and features. Although such features can influence the shading of the building surfaces, we did not assessed its impact in this work but can be evaluated in

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future works. In addition, indoor features such as the staircase, are not modelled here.

The room temperatures in winter and summer were set based on (Table 2) CIBSE Guide A (CIBSE, 2015) which recommended comfort criteria for specific types of building spaces.

The heating, cooling systems and infiltration were set as on continuously, and it was assumed that there was no natural ventilation. Occupancy schedule is one of the largest sources of error in building energy simulation process, because the occupants' behaviour is highly variable, and it is also difficult to predict (Ryan and Sanquist, 2012). Therefore, this research assumed that there is no occupant in the residential building when simulating the building performance.

According to Murphy (2011), the principle road should be wider than 8.80m, which included the cycle lane. The standard footway should be 2.00m wide, and each principle road should have two footways. Therefore, the total width of the road should be wider than 12.80m. In this research, the distance between the target building and the surrounding building was set to 15.00m.

The selected locations are Singapore, China-Beijing and Denmark-Copenhagen. These three locations were selected to investigate the influence of three different climatic conditions: tropical climate, humid continental and oceanic on the performance of the building under the same set conditions. The characteristics of these three locations and climate are detailed in Table 3. The impact of the arrangement of neighbouring buildings on the high-rise building performance is evaluated in this research.

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2.2 BES tool and theory

Building energy simulation (BES) has been used in the design process for predicting energy consumption and the building impact on the surrounding environment, which has become a widely accepted method during the design process (Ioannou and Itard, 2015). To reduce the building energy consumption, cost, environmental impacts and improve the thermal environment, dynamic thermal simulation programs are used in many studies (Maslesa et al., 2018, Garber) to achieve specific targets.

This research will use the BES tool Integrated Environmental Solutions (IES) Virtual Environment (VE) to assess the energy performance of the residential building. The BES is based on the commercial tool IES VE, which is a dynamic thermal simulation based on the modelling of the heat transfer processes between a building and its microclimate. The modelling of a commercial building using the IES VE tool was validated in previous work (Shahzad et al., 2018). Within the tool, the conduction, convection and radiation heat transfer processes for each building component or fabric are modelled individually and incorporated with the model of the heat gains, air exchange and plant within and around a thermal space or room.

For the discretization, the tool uses a finite difference approach to the heat diffusion equation solution, which first replaces the element with a finite number of discrete nodes at which the temperature will be calculated. The nodes are distributed within the layers for the modelling of the heat transfer and storage characteristics for the selected time step. This choice is based on constraints imposed on the Fourier number. Then, the time variable is discretized, and a combination between explicit and implicit time-stepping scheme is adopted to alternate

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nodes of the construction. The methods and approach used to model these processes are summarised here. The time-dependent spatial temperature distribution in a solid without internal heat sources is given by the partial differential equations:

$$W = -\lambda \nabla T \quad (1)$$

$$\nabla \cdot \mathrm{W} = -\rho \mathrm{c}_p \frac{\partial T}{\partial t} \quad (2)$$

where T is the temperature, W is the heat flux vector, λ is the conductivity, ρ is the density and c_p is the specific heat capacity. The heat storage in air masses or net heat flow into the air masses Q is modelled by the following equation:

$$\mathrm{Q} = \mathrm{c}_p \rho_a V \frac{\partial T_a}{\partial t} \quad (3)$$

where V is the air volume, ρ_a is the air density and T_a is the air temperature.

For the discretization, the tool uses a finite difference approach to the heat diffusion equation solution which first replaces the element with a finite number of discrete nodes at which the temperature will be calculated. The nodes are distributed within the layers for the modelling of the heat transfer and storage characteristics for the selected time step. This choice is based on constraints imposed on the Fourier number. Then, the time variable is discretized and a combination between explicit and implicit time-stepping scheme is adopted in order to alternate nodes of the construction. The convective heat transfer is described by the equation;

$$\mathrm{W}_{hf} = K(T_a - T_s)^n \quad (4)$$

where W_{hf} is the heat flux from the air to the surface, T_s is the mean surface temperature and K and n are coefficients.

The heat transfer rate associated with an air stream entering a space is described by equation;

$$Q = Mc_p(T_i - T_a) \tag{5}$$

where M is the air mass flow rate, T_i is the supply air temperature and T_a is the room mean air temperature.

For the interior long-wave radiation, the net radiant exchange between a surface and the rest of the enclosure is described by the equation;

$$W_{rl} = h_r(T_s - T_{MRT}) \tag{6}$$

where W_{rl} is the net radiative loss from the surface h_r is the surface heat transfer coefficient for exchange with the MRT node and T_{MRT} is the mean radiant temperature.

For the exterior long-wave radiation, the net long-wave gain for an external surface of inclination β (°) is represented by the following;

$$L^*(\beta) = \varepsilon_e \left[L_{skv}(\beta) + L_g(\beta) - \sigma\Theta_e^1 \right] \tag{7}$$

where ε_e is the emissivity of the exterior surface, $L_{skv}(\beta)$ is the long-wave radiation received directly from the sky, $L_g(\beta)$ is the long-wave radiation from the ground and Θ_e is the absolute temperature of the exterior surface. The tool calculates the solar flux incident on every external building surface at each time-step.

2.3 Parametric analysis

The isolated target building was located in Copenhagen, Beijing and Singapore, both thermal and energy performance were compared.

Eight surrounding buildings with the same height (33.6m) were added around the based building it as shown in Figure 2 (a). One location (Beijing) was selected for further energy performance comparison.

1. The number of surrounding buildings was reduced to four to analyse the impact of surrounding buildings' number. Surroundings were divided into two sets, named position a and position b, which are shown in Figure 2 (b).
2. The number of surrounding buildings was reduced to two. In this case, there were four conditions, named position a, position b, position c and position d, which are shown in Figure 3 (a).
3. Only one surrounding was placed next to the target building, and the surrounding building was located to the north, south, west, east, northwest, northeast, southwest and southeast, named position a, b, c, d, e, f, g, h, respectively, shown in Figure 3 (b).
4. Finally, the surrounding buildings' height was changed to 16.8m (half-height) and 67.2m (double-height) to analyse the impact by surrounding buildings' height, as shown in Figure 4.

3. Results and discussion

3.1 Impact of building location

The monthly heating and cooling energy demand of the three locations from simulation results are plotted in Figure 5.

The unit of the energy in this report is MWh (megawatt hour). The results show that in Singapore, although no heating was needed through the whole year, the cooling system operated from January to December, the annual cooling energy demand was 358.14MWh. The heating demand In Copenhagen was the largest as compared to the other two locations, and each month the cooling load was higher than 26.4MWh. Heating was needed for the whole year, and the peak heating load happened in January, which was 60.8MWh. The cooling demand in Copenhagen was much smaller than in Beijing. In Beijing, the heating load was 59.0MWh in January, and the cooling load was 26.4MWh in July. The heating period was longer than the cooling period.

Figure 6 and 7 show the solar gain of three locations and total energy demands. Although a large amount of solar gains could reduce heating load and increase the cooling load, there is minimal correlation between solar gain and total energy demand. Figure 6 shows that in Copenhagen, the solar gain in winter was much less than in summer, while in Beijing and Singapore, the difference was not that significant. Both heating and cooling set temperatures were close to the minimum and maximum average temperatures of Beijing, so the total loads were relatively low, especially in spring and autumn. Smaller temperature difference caused the lower temperature demand.

In Singapore, cooling is needed during the whole year under the set conditions. Kumar et al. (2020) suggested that the materials with high thermal mass can minimise and delay the indoor peak temperature by antiphasing with outdoor temperature, which can further reduce the summer overheating problem. High thermal mass insulations can be used to reduce the cooling energy demand in Siangpre. Similarly, these materials can also be applied to cold climate areas to keep a warm environment for the indoor. Additionally, Fantucci et al. (2019) and Huang et al. (2020) stated that compared to commonly used construction materials, the walls with low thermal conductivity insulations are thinner, which can save more floor space. To reduce the total energy load, well-insulated walls with low thermal conductivity should be selected.

The target building in three locations had the same indoor set conditions, Thermal comfort is evaluated by the predicted mean vote (PMV), which is developed by Fanger (1970). Predicted Percentage of Dissatisfied (PPD) is also used to show thermal comfort performance. Figure 9 shows that the PMV in Singapore was between 0.82 to 1.2, which means people would always feel slightly warm during the whole year. In order to minimise the PMV scale, the cooling set-point temperature should be lower than 24℃. However, this method will significantly increase the cooling energy demand.

In Beijing and Copenhagen, the tendencies of the PMV scale were similar to the outside temperature. People would feel slightly warm in summer and slightly cool in winter. The overall PMV scale of Copenhagen was the closest to 0, which can indicate that under the set condition, the indoor environment of Copenhagen was better than that in Beijing and Singapore.

Figure 9 also shows that about 25% occupants would feel uncomfortable in Singapore during the whole year, optimisations should be applied to improve the building thermal comfort performance by decreasing the indoor air temperature and humidity. In Beijing, people could be satisfied with the indoor environment in spring and autumn, the percentage of satisfaction in summer was higher than in winter. Buildings should be designed by considering both heat insulation and preservation (Binici et al., 2016), material types and thickness of insulation should be selected properly to improve energy efficiency and reduce greenhouse gas emission. Also, it is better to vary the heating and cooling set temperatures to provide a suitable

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indoor thermal environment.

Thermal comfort plays a pivotal part in the behaviours and perceptions of occupants; it also has an impact on the energy use in buildings (Wang, 2011). It is necessary to have a suitable control system to adjust the set condition according to the outside environment. In general, the indoor environment of residential buildings is not as constant as that of office buildings, because the interactions of occupants with the building components are difficult to estimate (BREEAM, 2016). Occupants can apply thermal adaptions to improve the comfort level of the indoor environment, such as adjusting the thermostat, changing their clothing or activity levels, using window shades, and opening or closing the windows.

Based on the above analysis, it shows that in Beijing, both heating and cooling energy were needed. It can clearly show how annual energy demands are impacted by the surrounding conditions. Until 2020, there are 43 buildings higher than 150m (CTBUH, 2020), which means high-rise building is one of the most common building types in Beijing. Therefore, Beijing was selected for the following analysis.

3.2 Impact of surrounding number and position

Monthly energy loads of the target building with eight surrounding buildings in Beijing are shown in Figure 10. A significant increase in heating energy demand was observed when the central building was shaded by similar height buildings. Without surrounding buildings, the annual solar gain was 199.21MWh, while with the eight surrounding buildings, the annual solar gain reduced to 122.93MWh. The results for May to September showed that cooling demand decreased when the target building was surrounded by other buildings. On average, the

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annual total energy demand increased by 7.82%. However, there were only cooling energy demand in summer, so the monthly total energy demand decreased from May to September.

Figure 11 compares the results of configuration a and b with four surrounding buildings. The building was located in the northern hemisphere and with the sun moving along the sun path from east to west, the direction of shadings would also change from northwest to northeast, so the surroundings located in position b could also increase the total energy load.

The surroundings in position a had a more significant impact on the target building's solar gain than position b. Therefore, surroundings in position a could increase by 5.04% of the total energy demand, and surroundings in position b could increase by 2.44%.

Figure 12 compares the results of configuration a-d with two surrounding buildings. It shows that the surrounding buildings in the north and south direction increased the building total energy demand much significantly than other three combinations, the annual solar reduced by 49.97MWh, which increased the heating load by 28.51MWh and decreased the cooling energy loads by 10.46MWh. The west and east surroundings had the smallest impact on the target building, and the total energy decreased by 0.51%, which was different from the other three configurations. As the latitude of Beijing is higher than the Tropic of Cancer, the solar radiation period in summer is longer than in winter. Therefore, with the surroundings in the west and east direction, the cooling load decrement in summer was larger than the heating load increment in winter.

For the net analysis, one surrounding building was located near the target building, the influence of each building position on the annual energy demand increment are summarised in

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Figure 13, and the annual energy loads and solar gain are shown in Figure 14.

Figure 14 shows that although the surrounding building in all positions reduced the target building's solar gain, the surrounding building only in south direction (including south, southwest and southeast) could increase the target building's total energy demand, and the surrounding building in other positions could decrease the total load. The result did not show a direct relationship between the annual total energy demand and solar gain. The change of annual total energy demand was determined as a result of the changing in both heating and cooling energy demands, and solar radiation can increase cooling energy demand and decrease heating energy demand. From Figure 14, it shows only when surrounding was located in position e had the largest impact on the target building's solar gain, which the solar gain reduction was 40.22MWh, and the target building's total energy demand increased 5.87%.

According to Figure 6, the monthly solar gain was high in Beijing, which means the solar radiation can help to reduce the heating energy demand in winter but increases the use of cooling energy in summer. It was mentioned by Cho et al. (2014), exterior shading devices for high-rise residential building can save about 20% cooling energy in Korea, and also improve the thermal comfort of the indoor environment. Figure 14 shows that only the surrounding in south direction (position e) can reduce a large amount of solar gain, which indicates that shading devices on building south side would be needed to reduce the solar gain and minimise the cooling energy demand in summer.

3.3 Impact of surrounding height

The height of surrounding buildings was varied to 16.8m and 67.2m and the results for the

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monthly heating and cooling loads of the target building are shown in Figure 15. Heating energy demand increased as the height of the surrounding buildings increased, and cooling energy demand decreased as the height of surrounding buildings decreased, as shown in Figure 15. Based on the cooling load results, it shows that the impact of half-height surroundings was much smaller than the same height and double-height surroundings. The increment of total energy demand for the 67.2m height surroundings was 10.17%, with 59.17% of the annual solar gain was reduced by the shadings of surrounding buildings.

Figure 16 shows the energy increment of the target building when only one surrounding building with three different heights located in the north, south, west and east.

The figure clearly shows that when the surrounding building's height increased, the south surrounding had the most significant impact on energy consumption. Comparing the heating energy demand increments in four positions, the influence of surroundings in the west and east sides were negligible when the surroundings' height increased in winter. However, if the surrounding located in the south, the heating load of the target building increased significantly when the surrounding's height doubled. Comparing the cooling energy demand, it shows that although the south surrounding can block more solar radiation for the target building than other three positions, the surroundings located in the west and east with 67.2m height can also reduce 2.2% cooling energy demand in summer. The surrounding buildings located in the north, west and east reduced the cooling energy demand of the target building in summer without causing a significant increment of heating energy demand in winter. Therefore, high buildings in the south direction which can block a large amount of solar radiation should be avoided during the

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planning stage, appropriate permanent shading devices can be added to the north, west and east walls and windows, which could help to provide a better indoor environment in summer.

4. Conclusion

The high-rise building energy demand thermal comfort and simulation tools are reviewed in this research. BES was used to analyse the performance of a high-rise residential building under different conditions. The energy demands and thermal comfort of the building in Copenhagen, Beijing and Singapore were compared. The impact of surrounding building number, height and position on the target building's energy performance were also discussed in detail.

The first step of this work was to analyse how the local climate affects building energy performance and indoor thermal comfort. It can be concluded that in Copenhagen, most energy would be used for heating the space, heating energy took up 97.58% of the total energy demand, while in Singapore, the energy was all used for cooling. Copenhagen had the largest monthly energy demand difference; the minimum monthly energy demand was 5.45MWh in June, and the maximum was 60.84MWh in January. Results will vary if occupants heat gain is considered. Under the same set conditions, there were great differences between PMV and PPD values among the three locations, which means the indoor set conditions should be determined depending on local environments.

The second step analysed how the number and position of surrounding buildings impact the central building's energy performance in Beijing. The larger the number of surroundings, the larger the total energy demand. Eight surroundings could increase the total energy demand by 7.82%. All surrounding buildings in different positions reduced the target building's solar gain, but the impact was different, the surrounding building in south direction had the largest impact (increased the target building's annual total energy demand by 5.87%).

The third step of this work compared the influence of eight surroundings with different height on the central building's energy performance in Beijing. The highest surroundings reduced 59.17% annual solar gain and added 10.17% total energy demand. The reduction of the central building's solar gain was significant. However, the energy demand increment by lower surroundings was only 2.32%. It indicates that for the buildings located in the centre of a large number of high buildings, the energy demand would be much higher than those without surroundings.

In conclusion, building energy performance can be affected by the height and position of the surrounding buildings. The impact can be both positive and negative. To improve the indoor thermal comfort and reduce energy consumption, appropriate insulation materials with high thermal mass should be selected to preserve the internal heat in winter and resist the external heat in summer. Permanent shading devices can be added to the north, west and east walls and windows of the residential building, because the shading effect provided by the surroundings in these positions can reduce the cooling energy demand of the target building in summer without causing a significant increment of heating energy demand in winter. These impacts should be taken into consideration when doing building design and urban planning.

5. Future work

In this research, weather data for simulation is the approximate climate based on the building

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location, while the actual microclimate condition would vary with the building position. The surroundings may affect the wind direction or the heat island effect caused by the dense buildings. The reflectively of neighbouring facades and heat island effect may also have additional impacts on building performance (Samuelson et al., 2016). In addition, it is also mentioned by Siu and Liao (2020) that past weather data cannot provide sufficient prediction to future weather events due to changes on climate and the most recent weather data may not be included in the weather files. IES does not simulate the effects of the urban environment on local wind patterns and air temperatures. Wind speed, wind direction, and air temperature are read from the weather file. Using weather files, however, can be problematic because the data typically come from meteorological stations at airports and military bases, sites far from the effects of the urban environment. In the best case, measured weather data from a location in the urban area may be used for more realistic conditions.

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Table 1. Construction materials specifications and U-values of the residential building

Component	Materials and thickness	U-value [W/m²K]	Solar absorptance	Solar resistance [m²K/W]
External walls	Cast concrete (dense) 150mm Insulation 50mm	0.51	0.7	0.04
Roof	Cast concrete (dense) 130mm Insulation 70mm	0.39	0.7	0.04
Floor slabs/ Ceiling	Cast concrete (dense) 140mm Insulation 60mm	0.43	0.55	0.1
Ground floor	Cast concrete (dense) 200mm Insulation 50mm	0.49	0.55	0.04
Internal partition	Plasterboard 60mm Insulation 40mm	0.53	0.55	0.13
Doors	Cork board 50mm	0.70	0.7	0.04

Component	Materials and thickness	U-value [W/m²K]	Transmission g-value	Solar absorptance	Solar resistance [m²K/W]
Windows	Clear float 8mm Cavity 12mm	2.88	0.75	0.837	0.04

Table 2. Set-point temperatures and infiltration value of the residential building

	Heating set-point	Cooling set-point	Infiltration
Bedrooms	18℃	24℃	0.5 ACH
Living rooms	22℃	24℃	0.5 ACH
Kitchen and washroom	20℃	24℃	0.5 ACH

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Table 3. Selected locations and climates for simulation [1]

	Beijing	Copenhagen	Singapore
Annual highest temperature	32°C	20°C	36°C
Annual lowest temperature	-8°C	-2°C	24°C
Climate type	Temperate	Cold	Hot-humid
Simulation weather location	Beijing International Airport	Copenhagen	Changi International Airport
Longitude and latitude	40.08°N, 116.59°E	55.62°N, 12.66°E	1.35°N, 103.99°E

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Figure 1. Layout, dimensions and room types of each floor of the residential building

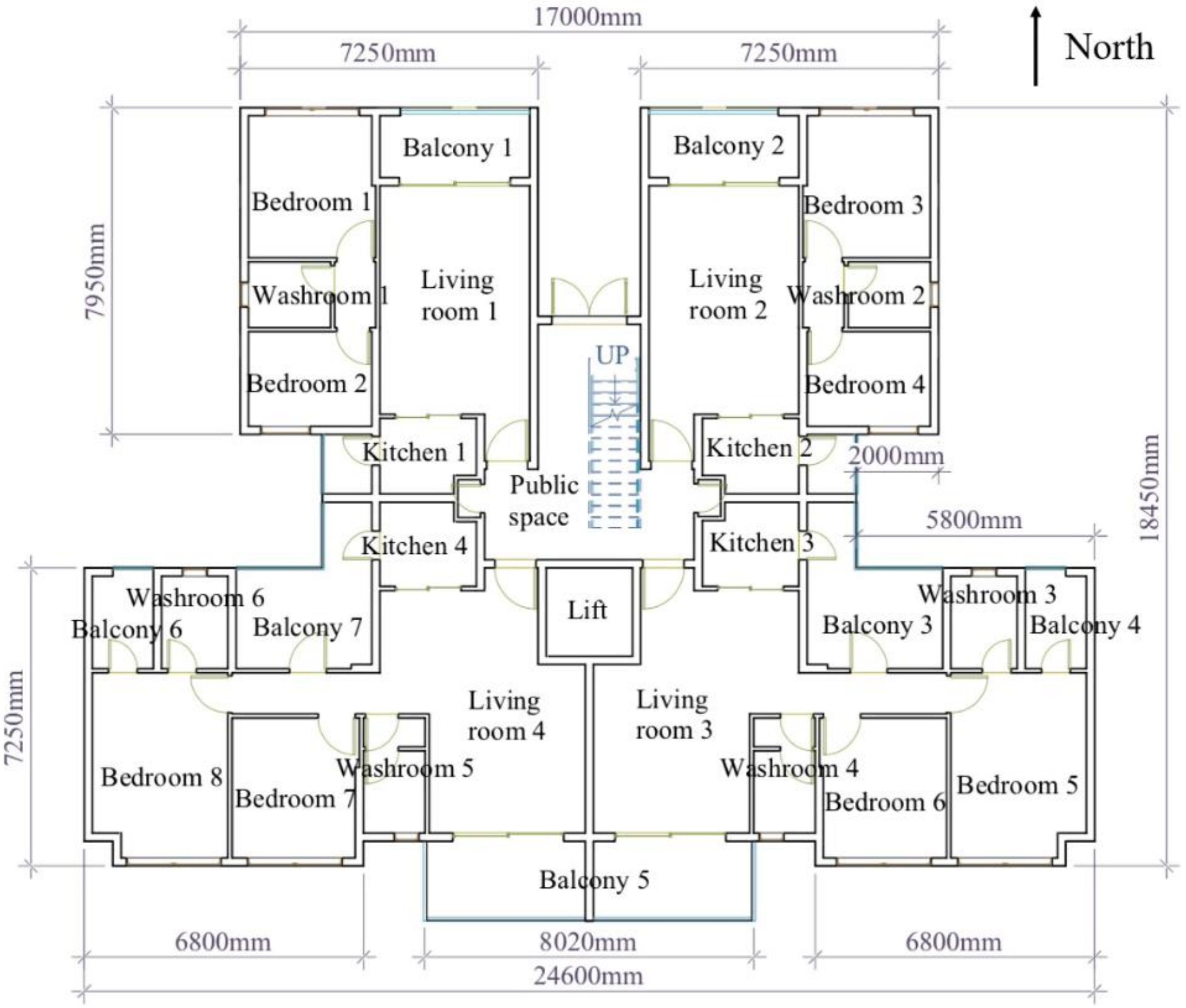
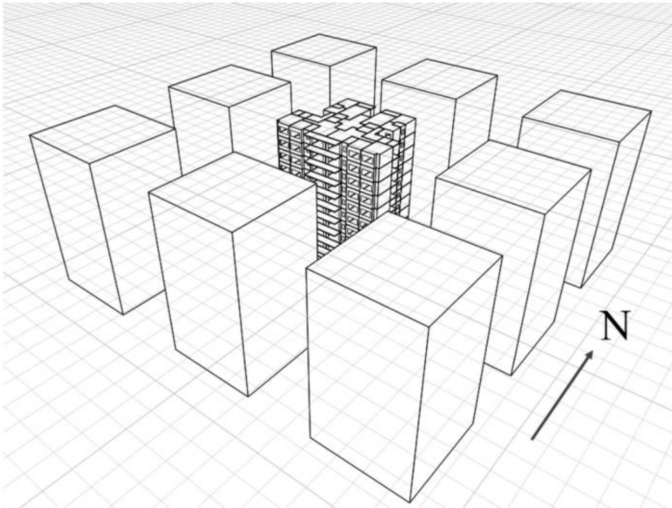


Figure 2. The condition that the residential building is surrounded by eight high-rise buildings, and the position names of the surroundings



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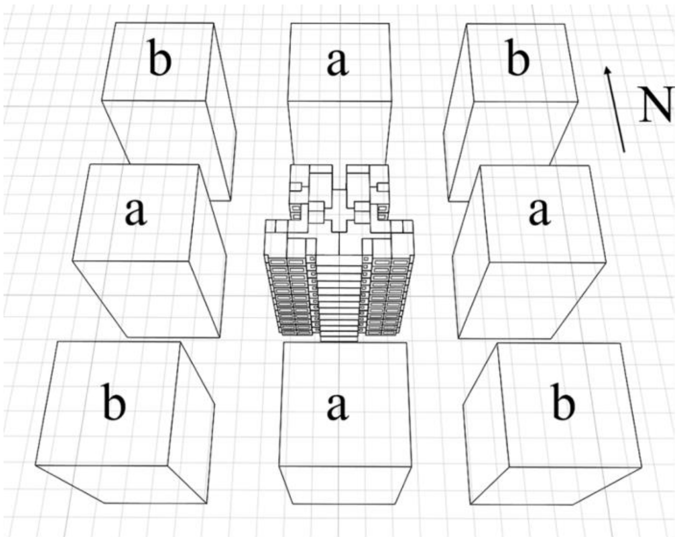

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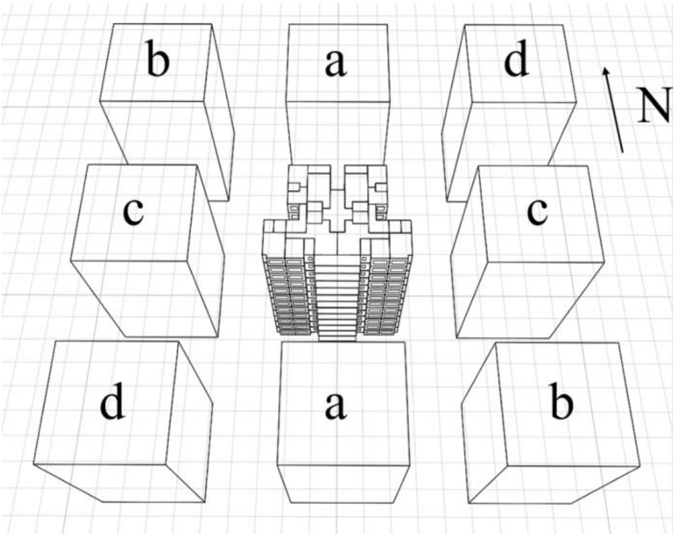
Figure 3. Position names of the surroundings when the surrounding buildings divided into four and eight sets



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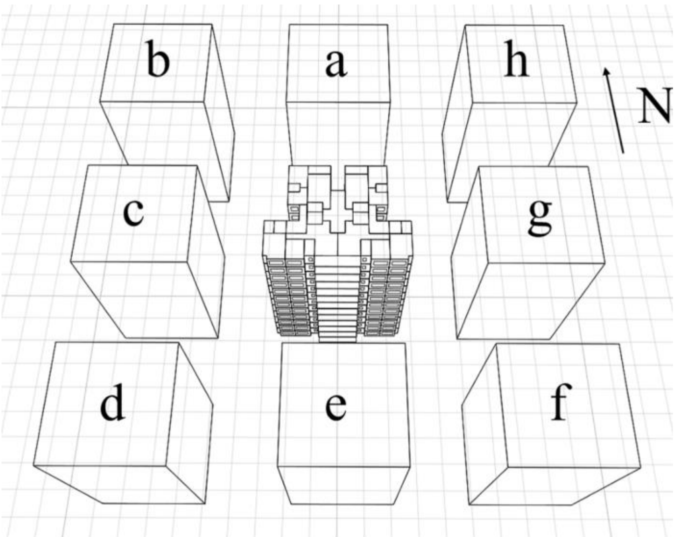

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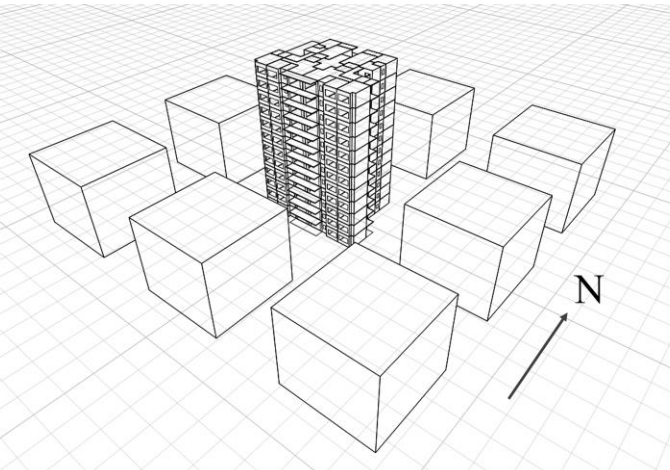
Figure 4. The condition that the residential building is surrounded by half-height and double-height surrounding structures



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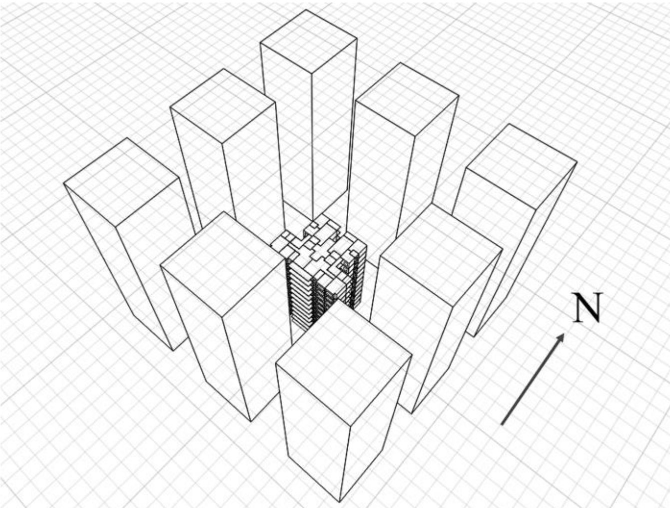

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Figure 5. Monthly heating and cooling energy demand of Copenhagen, Beijing and Singapore

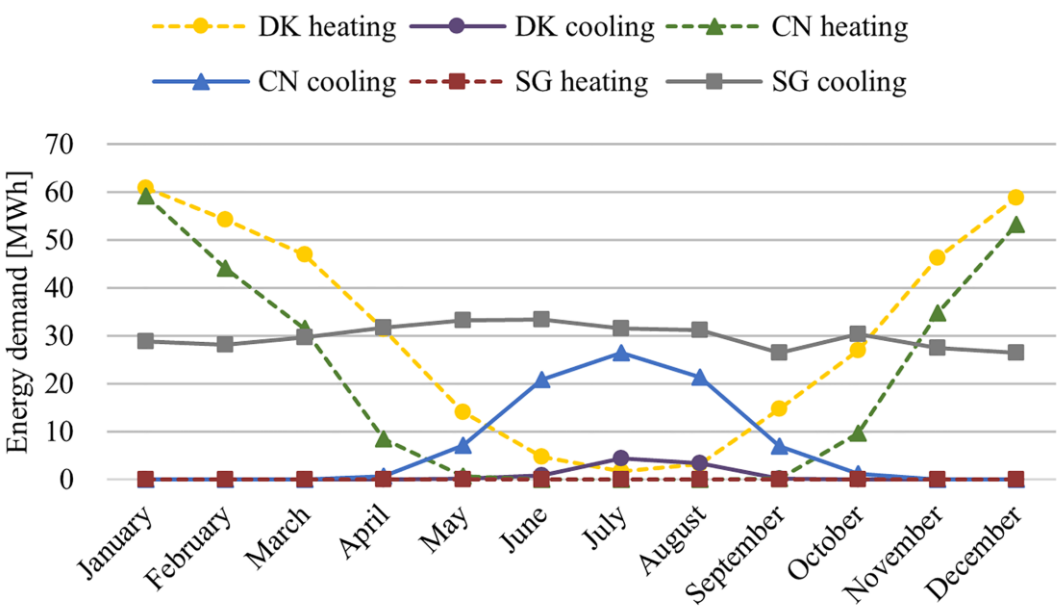

Figure 6. Monthly solar gain of Copenhagen, Beijing and Singapore

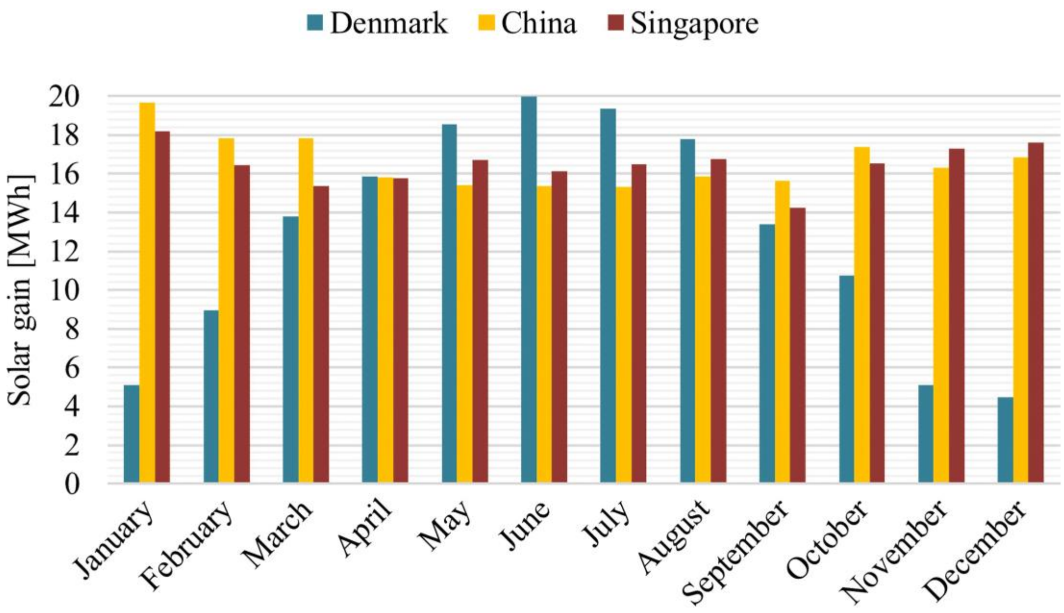

Figure 7. Monthly total energy demands of Predicted Percentage of Dissatisfied of Predicted Percentage of Dissatisfied of Figure 8: Predicted Mean Vote of Copenhagen, Beijing and Singapore, to show the thermal comfort level of the indoor environment

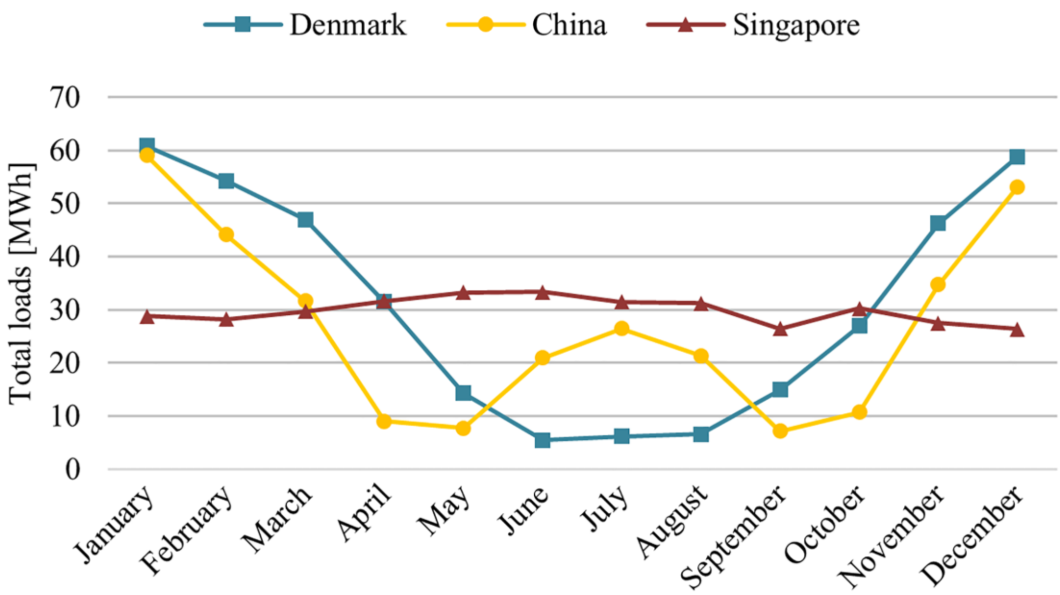

Figure 8. Predicted Mean Vote of the three locations

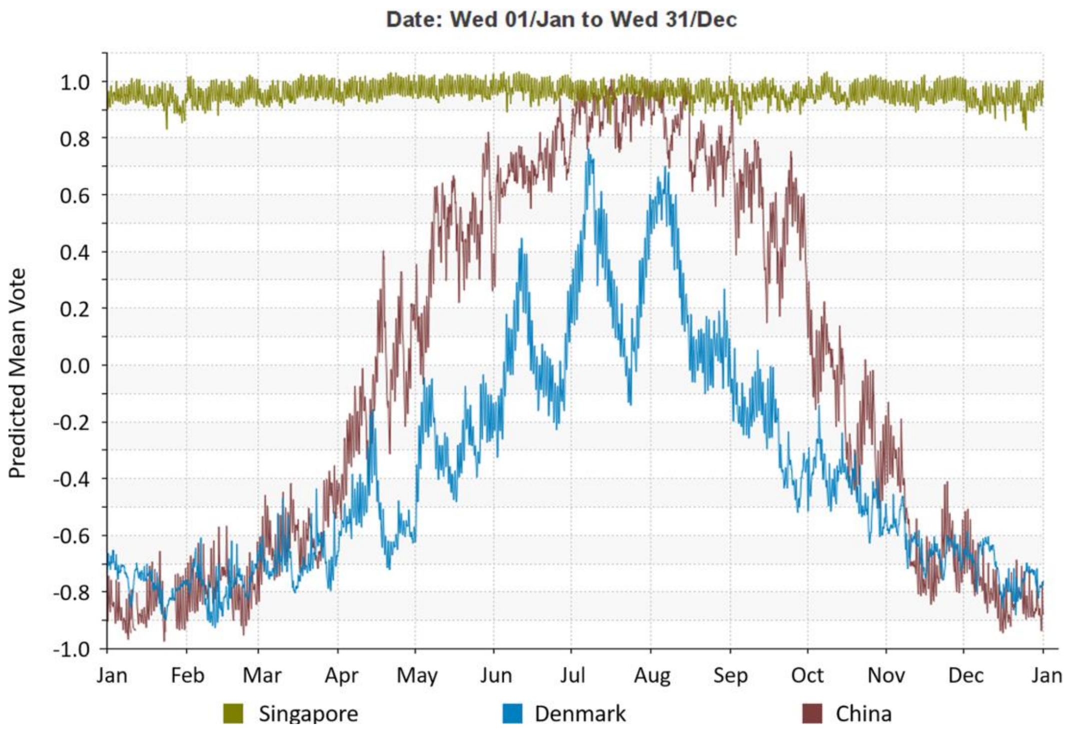

Figure 9. Predicted Percentage of Dissatisfied of Copenhagen, Beijing and Singapore, to show the how many percentages of occupants would feel dissatisfied under the set conditions

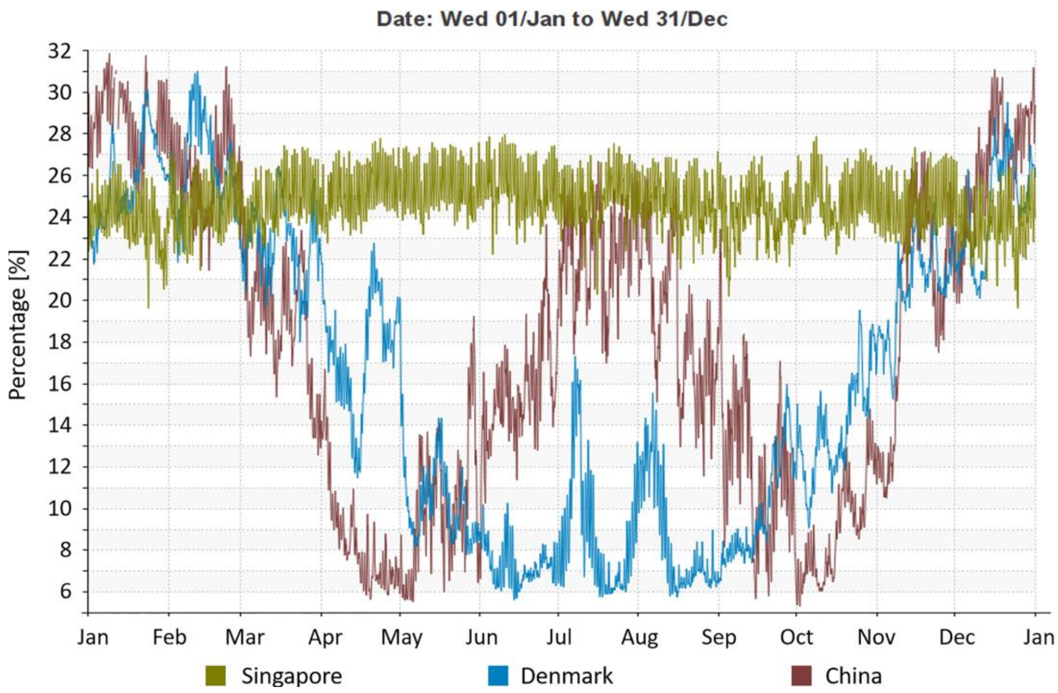

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Figure 10. Comparing the monthly energy consumption between no surrounding and eight surroundings to show how the surroundings have impact on the residential building's performance

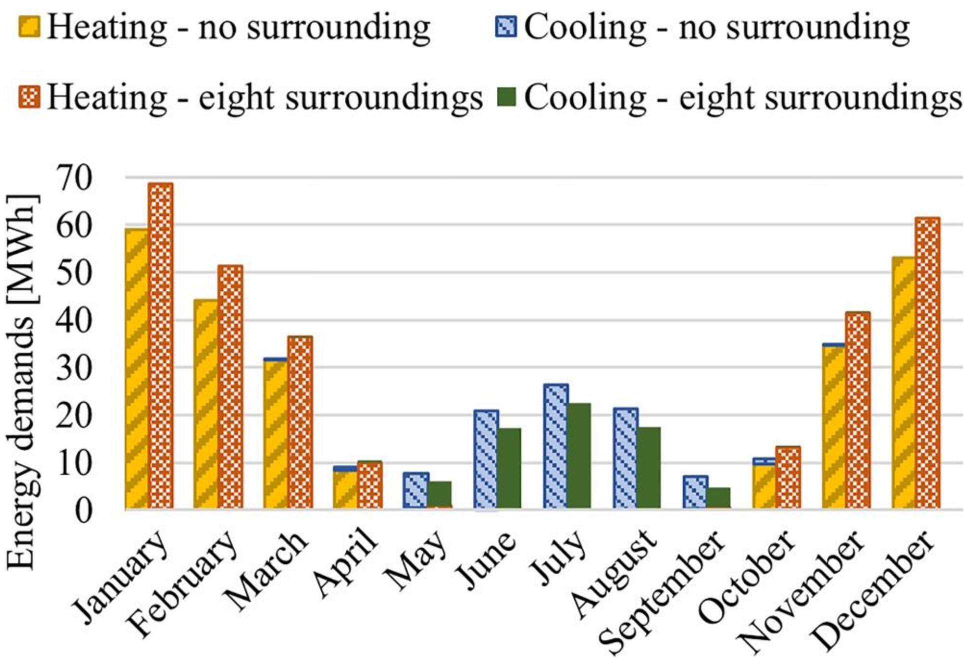

Figure 11. Influence of the four surrounding buildings in different positions on the residential building's annual total energy load in Beijing

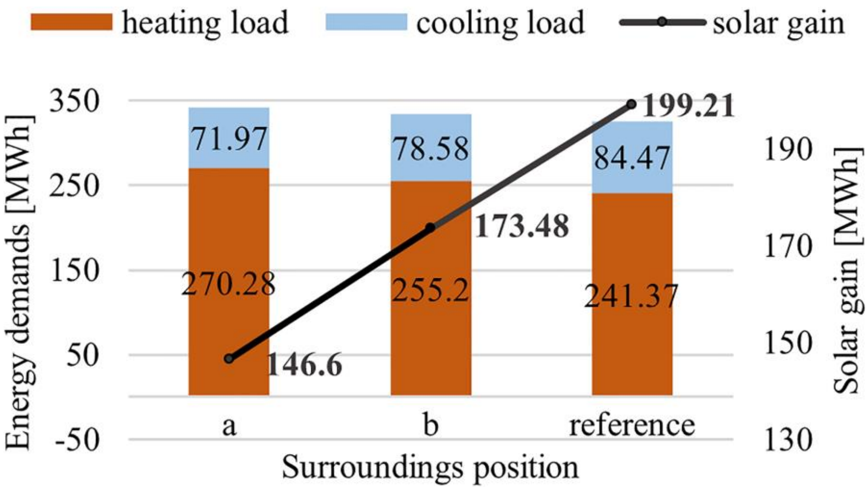

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Figure 12. Influence of the two surrounding buildings in different positions on the residential building's annual total energy load in Beijing

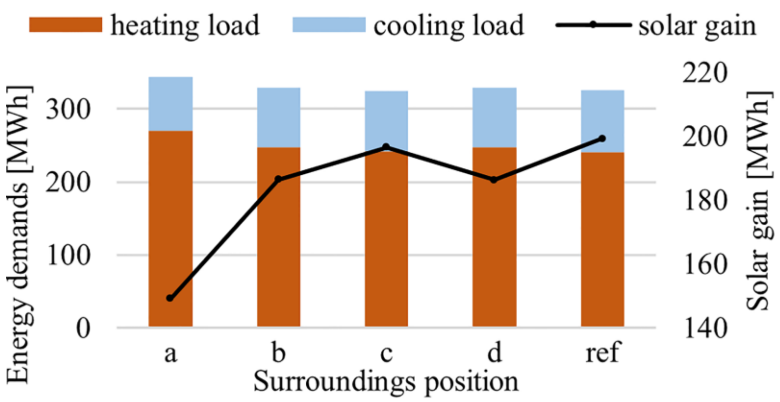

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Figure 13. Total energy increment of target building with surrounding in different positions, to show how much energy can be added to the residential building by the single surrounding in different positions

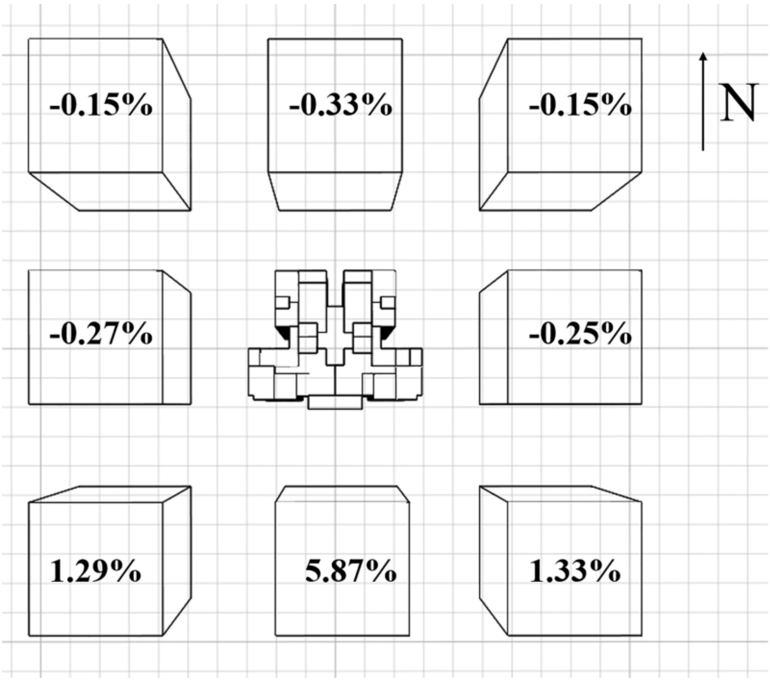

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Figure 14. Influence of the one surrounding building in different positions on the residential building's annual total energy load in Beijing

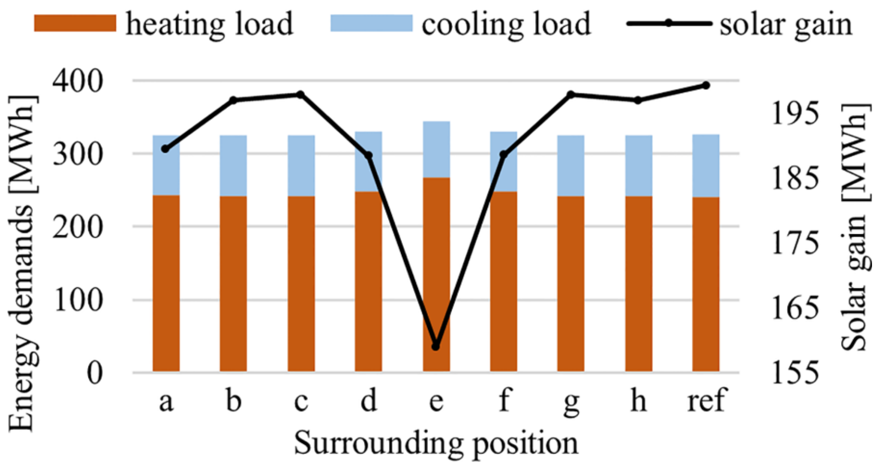

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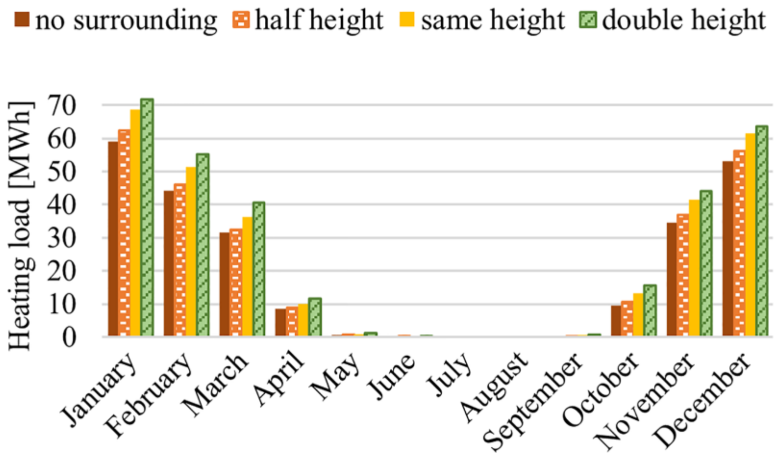
Figure 15. Monthly heating and cooling loads of target building with different height surroundings in Beijing, to show the energy performance difference caused by different height surroundings



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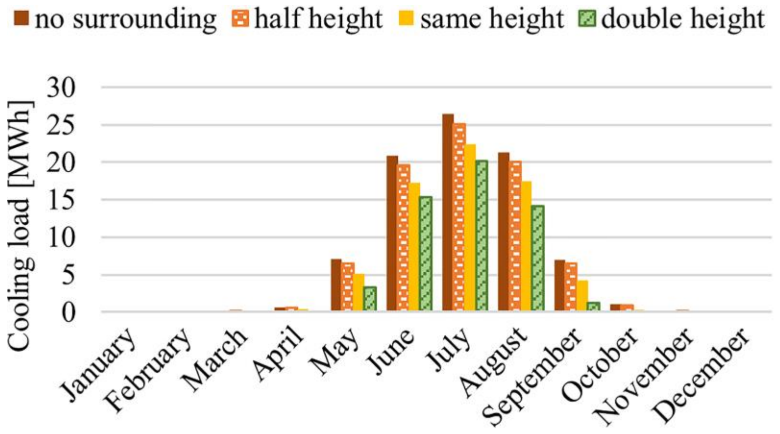

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Figure 16. Energy increment of the residential building when different height surroundings in north, south, west and east positions