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# Identification and comparison of key design parameters of high-rise and low-rise zero/low energy buildings in subtropical regions

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## ABSTRACT

Zero/low energy buildings, as an important means to facilitate the achievement of carbon neutrality, are receiving increasing attention worldwide. Numerous studies have been conducted to identify the key design parameters for zero/low energy buildings. However, these studies mainly focus on low-rise buildings. Few study has comprehensively investigated the key design parameters of high-rise buildings and compared with that of low-rise buildings, which is essential to achieve the zero /low energy buildings in cities with many high-rises. In this study, the key design parameters of high-rise and low-rise buildings in subtropical regions are identified by sensitivity analysis (SA), and the impacts of building height on the key building design focus are investigated. The SA is performed using Morris, in which a comprehensive consideration of 34 parameters (in 5 categories) affecting building performance are taken. The key design parameters affecting building energy consumption and winter thermal discomfort of high-rise and low-rise buildings in subtropical regions are identified respectively. Remarkable finding is that the overhang is the most influential element of the high-rise buildings, while skylight is the most influential element of the low-rise buildings concerning building energy consumption. The studied results may offer valuable references for the building envelope design in subtropical regions.

**Keywords:** zero/low energy building, sensitivity analysis, building envelope design, impact of building height, building energy consumption, thermal comfort

## NONMENCLATURE

| | |
|---|---|
| *Abbreviations* | |
| $U_T$ | Total assembly wall U-value (W/(m$^2$·K)) |
| $U_0$ | Wall U value (W/(m$^2$·K)) |
| $A_{tot}$ | total opaque wall area (m$^2$) |
| L | Length of a linear thermal transmittance (m) |
| $E_{tot}$ | Annual total building energy consumption (kWh) |
| $E_{CE}$ | Annual consumption for cooling (kWh) |
| $E_{LE}$ | Annual electricity consumption for lighting (kWh) |
| $E_{EE}$ | Annual electricity consumption for other electric equipment (kWh) |
| $f_{electricity}$ | Conversion factor converting electricity to primary energy (kWh/kWh) |
| $D_{dis}$ | Hourly thermal discomfort index |
| $PMV_{hourly}$ | Hourly PMV |
| *Symbols* | |
| $\Phi$ | Linear thermal transmittance (W/(m·K)) |
| $\chi$ | Point thermal transmittance (W/K) |

## 1. INTRODUCTION

Carbon neutrality is increasingly seen as the world's most urgent mission to limit global warming to well below 2°C compared to pre-industrial levels. Around 137 countries have committed to achieve carbon neutrality. The government of the Hong Kong SAR has also pledged to achieve net zero carbon emissions by 2050. Reducing energy demand and increasing renewable energy generation are the fundamental means to achieve the ambitious goal. Zero/low energy buildings with low energy demand and high utilization of renewable energy are therefore taken as effective means to facilitate the achievement of carbon neutrality, and are receiving increasing attention from government, society and professionals [1-2].

In recent years, many efforts have been made on identifying the key design parameters of zero/low energy buildings [3-8]. Lee et al. [4] performed sensitivity analysis to investigate the influential variables affecting the heating energy demand of the one-storey low-energy house in Korea. Li et al. [5] identified the key design parameters for design optimization of the zero/low energy buildings in subtropical regions based on a multi-stage sensitivity analysis approach.

Most of these research focus on the low-rise buildings which are easier to achieve zero/low energy goals. The key design parameters for high-rise buildings were seldom studied due to the constraints of the roof area, site coverage and structural load in these buildings [3]. However, with the fast urbanization process, the high-rise buildings have become the main force of the building energy efficiency, which can make a large number of energy conservation when achieving low energy buildings. Therefore, it is necessary to investigate on the key building design focus for the high-rise zero/low energy buildings.

In this study, the key design parameters of high-rise and low-rise buildings in subtropical regions are identified and their key design focus are compared. SA is performed using Morris, in which a comprehensive consideration of 34 parameters affecting building performance in 5 categories are taken. The key design parameters affecting building energy performance and winter thermal discomfort are without heating provision are identified respectively. The main contributions of this study include: (i). the identification of key design parameters of high-rise zero/low energy buildings in subtropical regions, and (ii). the investigation on the impacts of building height on key building design focus.

## 2. METHODOLOGIES

### *2.1 Approach and procedure of sensitivity analysis*

In this study, sensitivity analysis (SA) is conducted to identify the key design parameter for high-rise and low-rise buildings in subtropical regions. Hong Kong is determined as the typical city of subtropical regions. Morris, as a global SA method, is adopted due to its low calculation expense. The process of SA is illustrated in Fig. 1. At first, SimLab generates different input scenarios based on the concerned design parameters and their ranges. Secondly, JEPlus changes the parameter values in EnergyPlus building simulation model automatically and use. EnergyPlus to perform building performance simulation for each scenario. Finally, Simlab performs the SA based on the generated input scenarios and their corresponding performance.

### *2.2 Main design parameters of concern*

34 parameters are considered in SA, which can be classified into 5 categories: building layout and shape, envelope thermal characteristics, construction quality, system design and energy efficiency measures. The parameters and their ranges are summarized in Table 1. Some parameters related to energy system design are also included in the SA in order to identify the key design parameters related to building envelope based on a comprehensive comparison of their relative

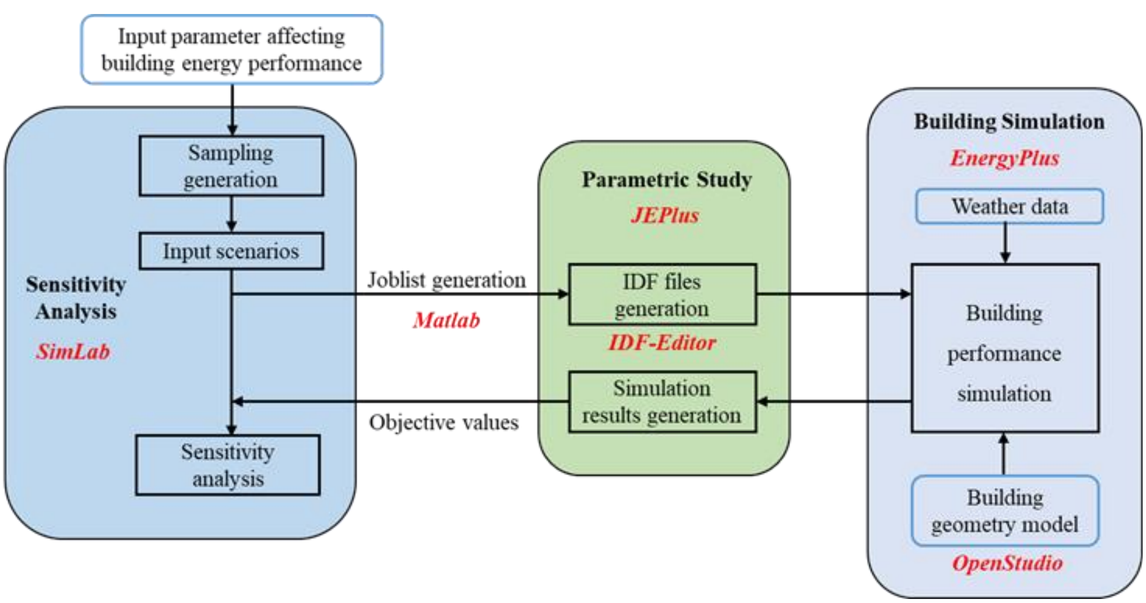
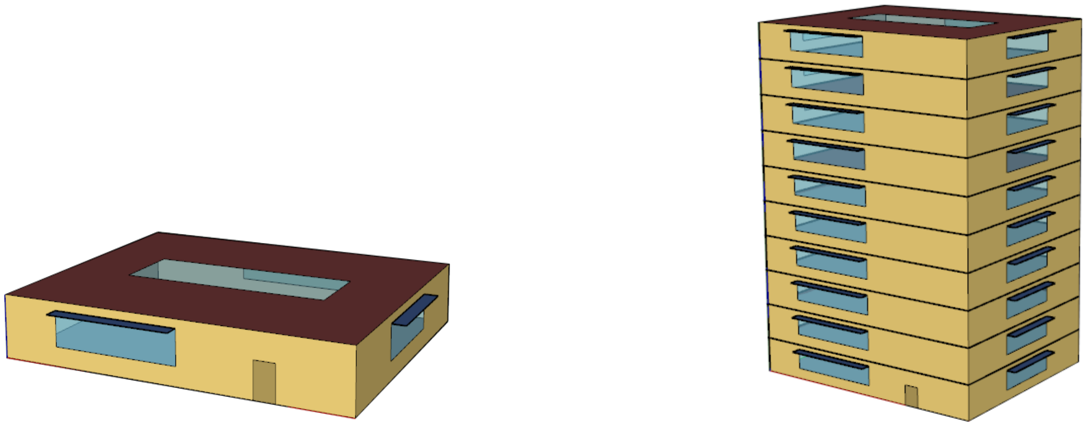



Fig 1 Procedure of sensitivity analysis.



(a) Low-rise building (b) High-rise building

Fig 2 Geometry models of high-rise and low-rise buildings.

significances. The parameters related to thermal bridge are integrated with the wall U-value and are determined as the overall wall U-value in the building performance simulation, as shown in Eq. (1) [9].

$$U_T = \frac{\sum(\varphi \cdot L)\sum(\times)}{A_{tot}} + U_0 \quad (1)$$

*2.3 Performance objective of sensitivity analysis*

In this study, the building performance is evaluated by not only the building energy consumption but also the winter thermal discomfort, as no heating is provided in Hong Kong. The performance objective related to building energy consumption is calculated by multiplying the annual electricity consumption for cooling ($E_{CE}$), lighting ($E_{LE}$) and other electric equipment ($E_{EE}$) by a primary energy conversion factor ($f_{eletricity}$), as formulated in Eq. (2). The performance objective used to evaluate the winter thermal discomfort is calculated by summing the hourly thermal discomfort index ($D_{dis}$) over the typical year. The thermal discomfort index is defined as Eq. (3)

$$E_{tot} = (E_{CE} + E_{LE} + E_{EE}) \cdot f_{electricity} \quad (2)$$

$$D_{dis} = \begin{cases} -0.5 - PMV_{hourly} & PMV_{hourly} < -0.5 \\ 0 & PMV_{hourly} \geq -0.5 \end{cases} \quad (3)$$

*2.4 Typical high-rise and low-rise buildings of concern*

Typical high-rise and low-rise office buildings are selected and considered for SA, (as shown in Fig. 2. The low-rise building is a one-story building, while the high-rise building is a ten-story building. The standard floor of the high-rise and low-rise buildings are set to the same for a more comparable analysis. The area of each standard floor is 500m$^2$ (25m×20m) and its height is 3.6m. The operating time of the buildings and energy systems is 8:00~20:00 on weekdays and 8:00~20:00 on Saturdays.

## 3. SENSITIVITY ANALYSIS RESULTS

*3.1 SA results for the high-rise buildings*

The sensitivity analysis results of the high-rise buildings in Hong Kong are shown in Fig.3 (a-b). In each figure, the top 20 highly sensitive parameters are listed. μ value represents the absolute value of elementary effects of a parameter. The larger the μ value is, the more significant the parameter is.

It can be seen from Fig.3 (a) that the building energy performance is mainly affected by the building envelope parameters. Although the most sensitive parameter is outdoor air flow rate, the other parameters of the top ten are related to overhang, window and wall. Furthermore, the overhang tilt angle has more significant impacts on building energy performance than overhang depth as fraction of height. As for the design parameters related to window, window visible light transmittance, window SHGC and WWR are the most sensitive. Among the design parameters related to wall, wall solar absorptance has more significant impacts than wall thermal absorptance. The skylight is also a crucial part of the high-rise buildings, and SRR and skylight SHGC are the highly sensitive ones.

Based on the SA results, the building energy performance of the high-rise is affected significantly by the outdoor fresh air, due to the significant difference between the indoor and outdoor temperature and humidity in this area. As a result, the outdoor airflow rate and infiltration air mass flowrate coefficient are more sensitive. Indoor setpoint temperature for cooling is the influential parameter related to energy system. The latent heat recovery effectiveness is also a key parameter influencing building energy performance because of the high outdoor air relative humidity.

In Hong Kong, the subtropical regions which are without heating provision in winter, the parameters affected winter thermal discomfort are identified for the high-rise as shown in Fig.3 (b). The most significant parameters are outdoor airflow rate and infiltration air mass flowrate coefficient, which are related to outdoor fresh air. As for the building envelope, the wall, window and skylight are the most essential parts. Wall thermal absorptance and wall solar absorptance, SHGC and area ratio of both window and skylight are the highly sensitive ones affecting both the winter thermal discomfort and building energy performance there. However, window U-

Table 1 Main design parameters and their ranges concerned for sensisity analysis.

| Category | Parameter (Unit) | Abbreviation | Value Range | Units |
|---|---|---|---|---|
| Layout and shape | Building Orientation | BO | 0~360 | ° |
| | Window to wall ratio | WWR | 0.1~0.9 | - |
| | Skylight to roof ratio | SRR | 0~0.9 | - |
| Envelope Thermal Characteristics | Wall U-value | WU | 0.09~ 11.1 | $W/(m^2·K)$ |
| | Wall specific heat | WSH | 800~2000 | J/( kg·K) |
| | Wall thermal absorptance | WTA | 0.1~0.9 | - |
| | Wall solar absorptance | WSA | 0.1~0.9 | - |
| | Wall visible absorptance | WVA | 0.1~0.9 | - |
| | Roof U-value | RU | 0.09~ 4.8 | $W/(m^2·K)$ |
| | Roof specific heat | RSH | 450~1400 | J (/kg·K) |
| | Roof thermal absorptance | RTA | 0.1~0.9 | - |
| | Roof solar absorptance | RSA | 0.1~0.9 | - |
| | Roof visible absorptance | RVA | 0.1~0.9 | - |
| | Ground slab U-value | GU | 0.15~2.27 | $W/(m^2·K)$ |
| | Ground slab specific heat | GSH | 800~2000 | J (/kg·K) |
| | Ground thermal absorptance | GTH | 0.1~0.9 | - |
| | Window U-value | WIU | 0.2~7.0 | $W/(m^2·K)$ |
| | Window SHGC | WSHGC | 0.1~0.9 | $W/(m^2·K)$ |
| | Window visible light transmittance | WVLT | 0.06, 0.1~0.9 | - |
| | Skylight U-value | SU | 0.2~7.0 | $W/(m^2·K)$ |
| | Skylight SHGC | SSHGC | 0.1~0.9 | $W/(m^2·K)$ |
| | Skylight visible light transmittance | SVLT | 0.06, 0.1~0.9 | - |
| Construction Quality | Infiltration air mass flowrate coefficient | IAMF | 1~1.5 | 1/h |
| | Floor slab linear thermal transmittance | FTLTT | 0.007~1.842 | W/(m·K) |
| | Glazing transition linear thermal transmittance | GTLTT | 0.030~1.058 | W/(m·K) |
| | Parapet linear thermal transmittance | PLTT | 0.056~1.060 | W/(m·K) |
| | Corner linear thermal transmittance | CLTT | 0.036~0.684 | W/(m·K) |
| | Interior wall intersection linear thermal transmittance | IILTT | 0.039~1.150 | W/(m·K) |
| System Design | Outdoor airflow rate | OAR | 0~0.02 | $m^3$/(person·s) |
| | Indoor setpoint temperature for cooling | STC | 22~28 | ℃ |
| Energy Efficient Measures | Overhang tilt angle | OTA | 0~180 | ° |
| | Overhang depth as fraction of window/door height | ODF | 0~3 | - |
| | Sensible heat recovery effectiveness | SHR | 0~0.9 | - |
| | Latent heat recovery effectiveness | LHR | 0~0.9 | - |

value is the key parameter affecting the winter thermal discomfort but not energy performance of the high-rise buildings.

*3.2 SA results for the low-rise buildings*

The sensitivity analysis results of the low-rise buildings are shown in Fig.4 (a-b) in which the top 20 highly sensitive parameters are listed. It can be seen from Fig.4 (a) that the building energy performance of the low-rise are mainly affected by the building envelope design, although the setpoint temperature for cooling is the most highly-sensitive parameter. The most influential design parameters of the low-rise are concerning the skylight and ground. The key parameters related to skylight are skylight SHGC, SRR and skylight U-value. The key parameter related to ground slab is ground slab U-value. The parameters related to solar protection and solar absorption are also important, such as overhang tilt angle, wall solar absorptance and roof solar absorptance.

Influential parameters to the building energy performance, which are not related to building envelope, include outdoor airflow rate, infiltration air mass flowrate coefficient and latent heat recovery effectiveness.

The indoor thermal discomfort of the low-rise buildings is mainly affected by the building envelope design and outdoor fresh air, which can be seen in Fig. 4 (b). The most influential parameters are all related to skylight, including skylight SHGC, SRR and skylight U-value, which are the same as the key parameters affecting the building energy performance. Wall and roof are also the important parts of the low-rise buildings. Outdoor airflow rate and infiltration air mass flowrate coefficient, which are related to outdoor fresh air are also the top sensitive parameters.

## *4. DISCUSSIONS*

It can be seen from Fig. 3 (a) and Fig. 4 (a) that no matter the high-rise buildings or low-rise buildings, outdoor airflow rate, indoor setpoint temperature for cooling, latent heat recovery effectiveness and infiltration air mass flowrate coefficient are the top sensitive parameters due to the significant difference between the indoor and outdoor temperature and humidity in subtropical regions.

The building envelope design parameters affecting building energy performance of high-rise and low-rise buildings are significantly different, which determines the different design focus of them. Overhang is the most important part for the high-rise buildings, while skylight is the most important envelope for the low-rise buildings. The key parameters related to overhang including overhang tilt angle and overhang depth as fraction of height, and overhang tilt angle, are always more influential than overhang depth as fraction of height. Skylight SHGC, SRR and skylight U-value are the key design parameters related to skylight of low-rise buildings.

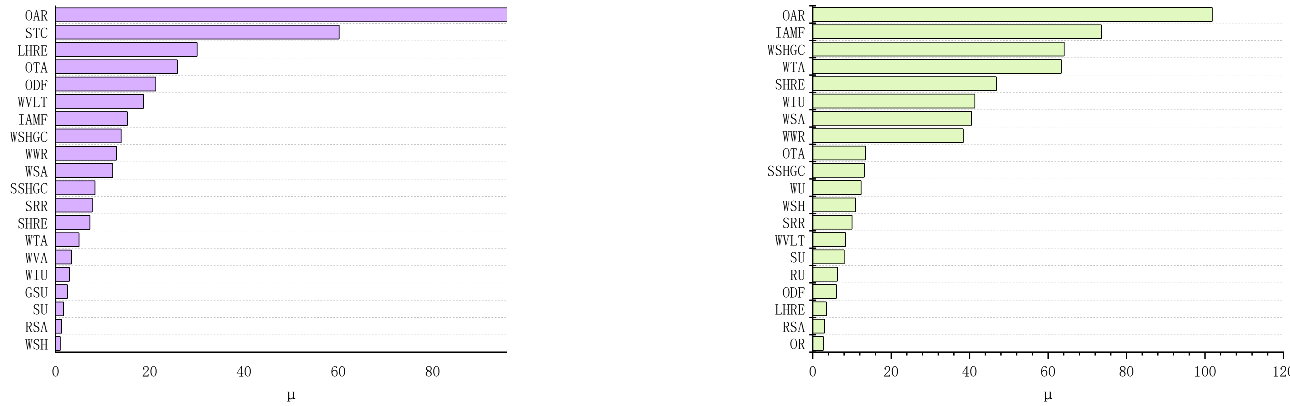
As for the parameters influencing the winter thermal discomfort, the top parameters are related to outdoor fresh air including outdoor airflow rate and infiltration air mass flowrate coefficient. As for the high-rise buildings, the wall, window, overhang and skylight are the influential part on both the winter thermal discomfort and the building energy performance. As for the low-rise buildings, the design parameters of skylight is the most influential, followed by the design parameters related to wall and roof.

It should be noted that the key design parameters of high-rise and low-rise buildings in subtropical regions are identified using Hong Kong as the typical city of subtropical regions in this study. The results may be slightly different for other cities in the subtropical regions.

## 5. CONCLUSIONS

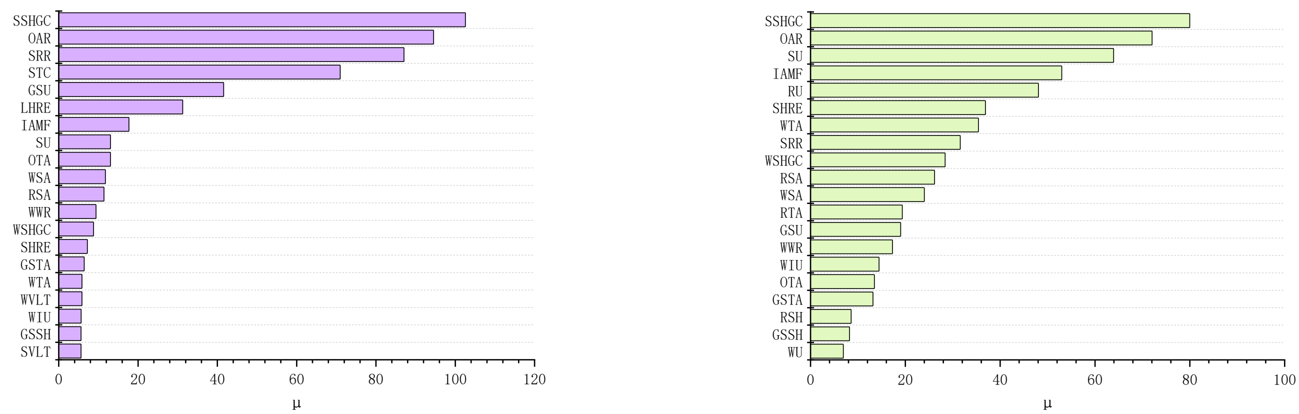
In this study, the key design parameters affecting building energy performance and winter thermal discomfort of high-rise and low-rise buildings in subtropical regions are identified and the key design focus of them are compared. Based on the sensitivity analysis results, conclusions can be made and summarized as follows.

The building envelope design parameters affecting building energy performance for the high-rise and low-rise buildings are significantly different, which determines the different design focus of them. The design of overhang is the most influential part for the high-rise buildings, while skylight is the most influential for the low-rise buildings. The overhang tilt angle is always more significant than overhang depth as fraction of height. Skylight SHGC, SRR and skylight U-value are the key design parameters related to skylight of low-rise buildings.




(a) Building energy performance (b) Winter thermal discomfort

Fig 3 Highly sensitive (top 20) parameters affecting building performance of the high-rise building.




(a) Building energy performance (b) Winter thermal discomfort

Fig 4 Highly sensitive (top 20) parameters affecting building performance of the low-rise building.

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