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The influence of building envelope design on the thermal comfort of high-rise residential buildings in Hong Kong

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Abstract: Combined effects of climate change and rapid urbanisation make buildings in high-density cities vulnerable to overheating, and thus induce high cooling energy demand, especially during the more frequently occurring near-extreme conditions in summer. It is necessary to minimise building energy consumption without compromising the comfort of occupants by adopting climate-adaptive building envelope designs. By employing the summer reference year weather data for building simulations, this study examines how the indoor thermal comfort of free-running high-rise buildings in subtropical Hong Kong may be affected by modifications of the wall U-value, the depth of window overhang shading, and the window-to-wall ratio (WWR). Results show that better insulated flats experience less extreme thermal conditions but maintain a warmer-than-comfortable indoor environment, while flats with appropriate shading enjoy a net improvement in thermal comfort, especially for eastward and westward facing flats. When considering the WWR, thermal comfort can be maximised by placing windows strategically to facilitate cross-ventilation. Nevertheless, none of the models are able to achieve comfortable conditions for over 40% of the summertime. Further work is required to explore the potential of combined passive strategies or mixed-mode ventilation in optimising building performance and providing thermal comfort for occupants under future climate change.

Keywords: Building envelope design, Indoor thermal comfort, Building simulation, Summer reference year (SRY), High-rise residential buildings

1. Introduction

Indoor thermal comfort has long been an important area of research because of its well-established links with building occupants' well-being and health (Ortiz et al., 2017). As the urban population continues to grow worldwide, many cities are now dominated by high-density developments, with Hong Kong being a prime example where people commonly reside in high-rise apartment buildings. However, the indoor thermal environment of such compact living spaces is susceptible to overheating due to intense solar radiation, poor ventilation, and the slow release of heat from building materials, particularly during the hot and humid summers in Hong Kong. People thus rely heavily on air-conditioning to maintain thermal comfort, as reflected by the continued increase in electricity consumption by the domestic sector (HKCSD, 2016). The more frequent occurrence of extreme hot weather brought by climate change further exacerbates the urban heat island effects and incurs higher energy demand. In order to minimise energy consumption without compromising the comfort of occupants, there is an obvious need to optimise building performance by adopting climate-adaptive building design strategies.

Multiple efforts have been made by the local government and research communities to improve energy efficiency in high-rise residential buildings in Hong Kong (Ma and Wang, 2009). Modifications on glazing and wall insulation (Bojic et al., 2001; Cheung et al., 2005; Bojic and Yik, 2007) have been investigated in earlier studies, while others have explored the use of intelligent building control systems to balance comfort and energy use (Shaikh et al., 2014). In hot and humid climates, solar heat gain from total window area and heat transfer through building façades were found to have the most considerable effects on building energy performance (Yildiz and Arsan, 2011), as is the case for Hong Kong (Chen et al., 2015). In the last two decades, Building Energy Codes were introduced by the Hong Kong Government (Chan and Yeung, 2005) to regulate energy use in buildings, including the mandatory control on Overall Thermal Transfer Values, which recognizes the importance of managing outdoor-to-indoor heat transfer through the external envelope of buildings (Lam et al., 2005). Concurrently, the Hong Kong Building Environmental Assessment Method (BEAM) was initiated by the private sector to promote environmental friendly building designs, construction, operation, and management. An alternative passive design route for buildings to achieve credits for certification by considering site aspects, daylighting, natural ventilation, envelope heat transfer etc., was recently made available (BEAM Society Limited, 2012; Chen et al., 2015). There have also been an increasing number of studies on the effectiveness of passive design strategies and naturally ventilated buildings in Hong Kong (Haase and Amato, 2009; Gao and Lee, 2011; Chen et al., 2017). Nevertheless, few focused on the more fundamental relationship between building envelope parameters and thermal comfort of indoor environments under free-running conditions, nor have the added warming effects of climate change been taken into account in previous parametric studies.

In light of the knowledge gap identified, this study aims to examine how modifications of various building envelope parameters correlate with measures of indoor thermal comfort under near-extreme summer conditions in hot and humid Hong Kong. The responses for flats of different orientations will also be investigated. A brief discussion on the effectiveness and limitations of various design strategies for high-rise residential buildings will then be presented.

2. Methodology

This study was conducted by performing building simulations with EnergyPlus on the DesignBuilder software platform. EnergyPlus is a dynamic simulation engine used by the Department of Energy in the United States for internationally recognized building assessments and its robustness have been well-validated by field measurements (Shrestha and Maxwell, 2011; Mateus et al., 2014) as well as the Building Energy Simulation TEST procedure (Judkoff and Neymark, 1995). Hourly weather data of the Summer Reference Year (SRY) of Hong Kong, which has been statistically adjusted from the Test Reference Year to represent near-extreme summer conditions (Lau et al., 2017), were used as inputs for the building simulations. Results for the three hottest summer months, from June to August, were then extracted from annual simulations for subsequent analyses.

2.1. Baseline building model

Public rental housing (PRH) accommodates around half of the total population in Hong Kong (HKHA, 2016), and cross-shaped buildings with 40 or more storeys are common in newer generation PRH estates. Therefore, the baseline building model was constructed based on the Concord type PRH, as shown in Figure 1a. Windows were assumed to have a height (sill to head) of 1.9m. To reduce the computational cost required, the building layout was simplified to eight identical flats and only the living rooms and bedrooms were included in thermal calculations of flats (Figure 1b). Furthermore, as the middle floor is considered sufficient to represent the average performance of a high-rise building (Chen et al., 2015), the rest of the building was constructed using adiabatic component blocks.

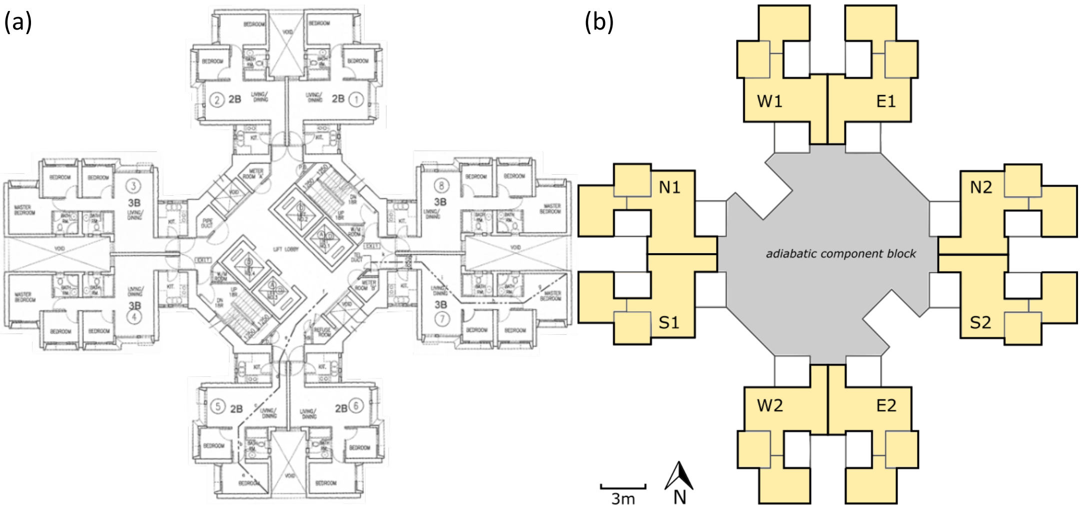


Figure 1. (a) Building layout plan of a Concord type PRH and (b) a simplified layout used for building simulation (only the parts highlighted in yellow were considered in thermal calculations). Flats facing different orientations are labelled accordingly.

Building model properties were set according to the BEAM Plus New Buildings Version 1.2 manual (BEAM Society Limited, 2012). Table 1 shows the detailed characteristics of the construction materials. The window-to-wall ratio (WWR) for baseline residential buildings was defined to be 0.4. The building occupancy schedule was set according to survey findings by Chen and Lee (2010) and an occupant density of 0.083 people/m^2 was adopted to reflect typical high-density living conditions in public housing estates in Hong Kong (HKHA, 2016). As this study focuses only on the effects of passive designs under free-running conditions and not the heating, ventilation and air conditioning (HVAC) systems of buildings, the windows were assumed to be 30% opened all the time regardless of outdoor temperatures and no mechanical ventilation was applied.

Table 1. Properties of construction materials for the building envelope of the baseline building model, where k is thermal conductivity, ρ is density, C_p is specific heat, α is solar absorptivity of exposed surface (adapted from BEAM Society Limited, 2012).

	Thickness (m)	Material	k (W/mK)	ρ (kg/m^3)	C_p (J/kgK)	α (-)
External Walls						
Layer 1 (exterior)	0.005	Mosaic Tiles	1.5	2500	840	0.58
Layer 2	0.01	Cement/Sand Plastering	0.72	1860	840	
Layer 3	0.1	Heavy Concrete	2.16	2400	840	
Layer 4 (interior)	0.01	Gypsum Plastering	0.38	1120	840	0.65
Floor/Ceiling (middle floor flats)						
Layer 1	0.01	Gypsum Plasterboard	0.38	1120	837	
Layer 2	0.18	Reinforced Concrete	1.9	2300	840	
Layer 3	0.01	Floor Tiles	0.8	1700	850	
Windows						
Layer 1	0.006	Tinted Glass	1.05	2500	840	0.65

2.2. Building envelope parameters

The majority of heat gain or loss of a building is contributed by the building envelope, which functions to protect and moderate the climate of the indoor environment (Mirrahimi et al., 2016). It comprises the external wall, roof, floor, glazing, and shading, and the amount of heat transfer is dependent on the physical building form and design, as well as its orientation. Lam et al. (2005) identified solar heat gain through windows as the dominant source of heat gain for buildings in subtropical Hong Kong. Reducing window areas and employing appropriate shading devices may be effective in minimising the direct solar radiation indoors and hence improve internal thermal conditions (Al-Tamimi and Fadzil, 2011). Window designs were also found to perform better on the west and east orientations, and the worst for windows facing north (Huang et al., 2014). Besides, previous research showed that thinner external walls with higher U-values are less capable of regulating indoor temperatures, resulting in more intense and longer durations of discomfort felt by occupants (Kwok et al., 2017).

Impacts of construction material properties, window sizes, and shading devices on the indoor thermal comfort of naturally-ventilated buildings in hot-humid climates have often been investigated (Wang and Wong, 2007). With an understanding of the significant components of a building envelope, selected parameters, namely the wall U-value, the depth of window overhang shading, and the WWR, were modified separately on the baseline building model of Hong Kong. The various configurations evaluated in this study are listed in Table 2.

Table 2. Details of the building envelope parameters studied.

Model	Wall U-value (W/m^2K) *concrete thickness (m)*	Depth of overhang shading (m)	Window-to-wall ratio (-)
BL[a]	3.849 *(0.1)*	0	0.4
U15	3.534 *(0.15)*	0	0.4
U20	3.267 *(0.2)*		
U25	3.037 *(0.25)*		
U30	2.837 *(0.3)*		
O03	3.849 *(0.1)*	0.3	0.4
O06		0.6	
O09		0.9	
O12		1.2	
O15		1.5[b]	
Rmin	3.849 *(0.1)*	0	0.033[c]
R01			0.1
R02			0.2
R03			0.3

a. baseline model (BL) constructed according to BEAM Plus New Buildings Version 1.2 manual (BEAM Society Limited, 2012)

b. based on guidelines for effective shading that overhanging projection should be equal to or less than 1.5m from the external wall surface (HKBD, 2014)

c. based on statutory requirement in APP-130 that total area of primary openings should not be less than 1/16 of the floor area of the room (HKBD, 2016)

2.3. Measures of thermal comfort

The indoor thermal comfort was described using the Predicted Mean Vote (PMV) index (Fanger, 1970) and operative temperatures (T_{op}). Human thermal sensations from very cold (-3) to very hot (+3) were calculated within DesignBuilder according to the ISO standard 7730 (2005), with the metabolic rate and clothing index assumed to be 0.9 met and 0.3 clo, respectively. As a result of acclimatisation, people living in hot-humid climates have often reported neutral temperatures higher than that predicted by the PMV model (Djamila et al., 2013). To account for such a discrepancy, an extended PMV model incorporating an expectancy factor 'e' was developed for predicting the actual votes of occupants living in non-air-conditioned buildings in warm climates (Fanger and Toftum, 2002). This approach has previously been applied with e = 0.7 for evaluating the thermal comfort of PRH flats in Hong Kong (Kwok et al., 2017). Throughout this study, positive PMV values were also multiplied by an expectancy factor of 0.7. On the other hand, T_{op} was used to reflect the physical thermal environment felt by occupants within a flat. T_{op} was preferred as a measure of thermal comfort as it is able to represent effects of both convective and radiative heat transfer. For occupants with sedentary behaviours who are not exposed to direct sunlight and strong air flow, T_{op} can be approximated by the averaging the simulated air and radiant temperatures (ASHRAE Standard, 2004).

3. Results

3.1. Baseline model and effects of building orientation

Operative temperatures (T_{op}) for each hour of the day, averaged over simulation results from June to August of the SRY, are plotted in Figure 2 to show the diurnal variations of T_{op} for flats facing different orientations (refer to Figure 1 for the labelling of flats). Flats facing the east (E1, E2) and the west (W1, W2) generally exhibit higher T_{op} due to direct solar radiation from the low angle sun during sunrise and sunset. Eastward facing flats warm up the fastest in the day, while westward facing flats have the highest T_{op} in the late afternoon and remain the hottest throughout the night. Flats facing the west reach the highest average daily maximum T_{op} (up to 31.4°C) at around 6pm, which is over 0.6°C higher than that of flats facing the north or the south. A similar diurnal variation pattern and a relatively small daily temperature range can be observed for all northward and southward facing flats (N1, N2, S1, S2).

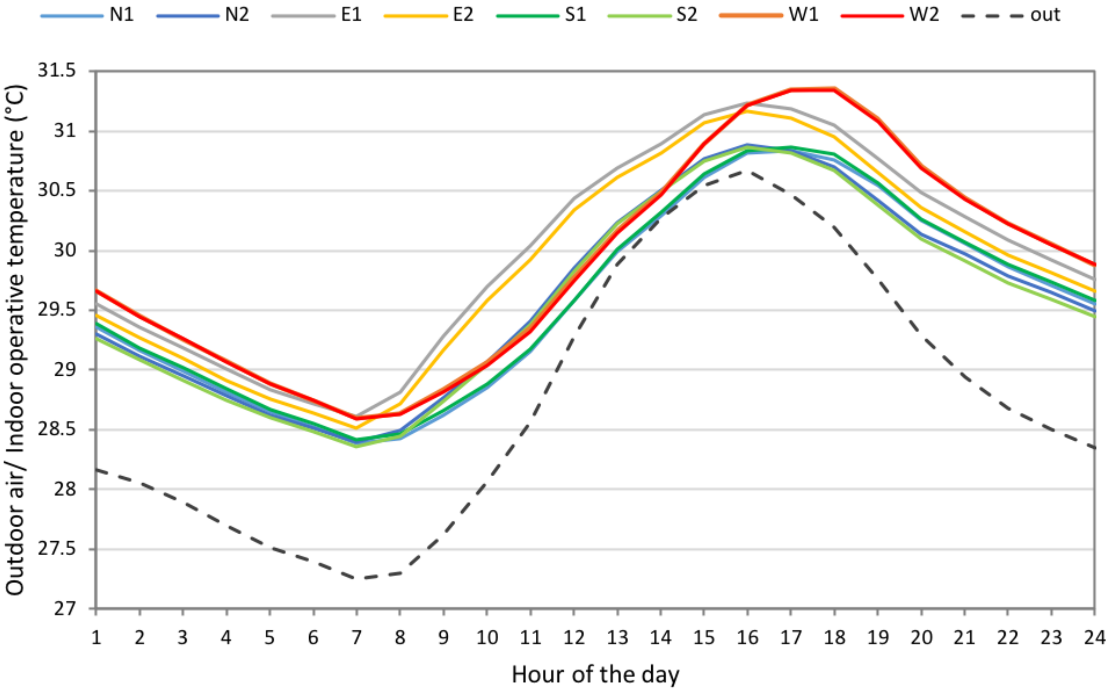


Figure 2. Diurnal variations of outdoor air temperature and T_{op} for flats facing different orientations in the baseline building model, averaged over June to August of the SRY.

Figure 3 shows the predicted thermal sensations of occupants and their corresponding amount of time felt in flats of different orientations in the baseline building model. PMV values were calculated based on the adjusted PMV model with e = 0.7. Since flats were simulated under free-running conditions, highly variable indoor thermal environments from PMV less than -0.5 (slightly cold to cold) to more than +2 (very hot) can be observed. Occupants feel warm to hot (PMV +0.5 to +1.5) for the majority of time during a near-extreme summer in Hong Kong. Flats of northern and southern orientations provide comfortable thermal conditions (PMV -0.5 to +0.5) for around 30% of the time, whereas occupants in flats of eastern and western orientations are only comfortable for around 25% of the time. The latter are even exposed to very hot conditions (PMV +1.5 or above) up to 16% of the time and should be given particular attention when designing for indoor thermal comfort. Therefore, the following parametric analyses will mainly focus on flats facing the east (E flats) and the west (W flats).

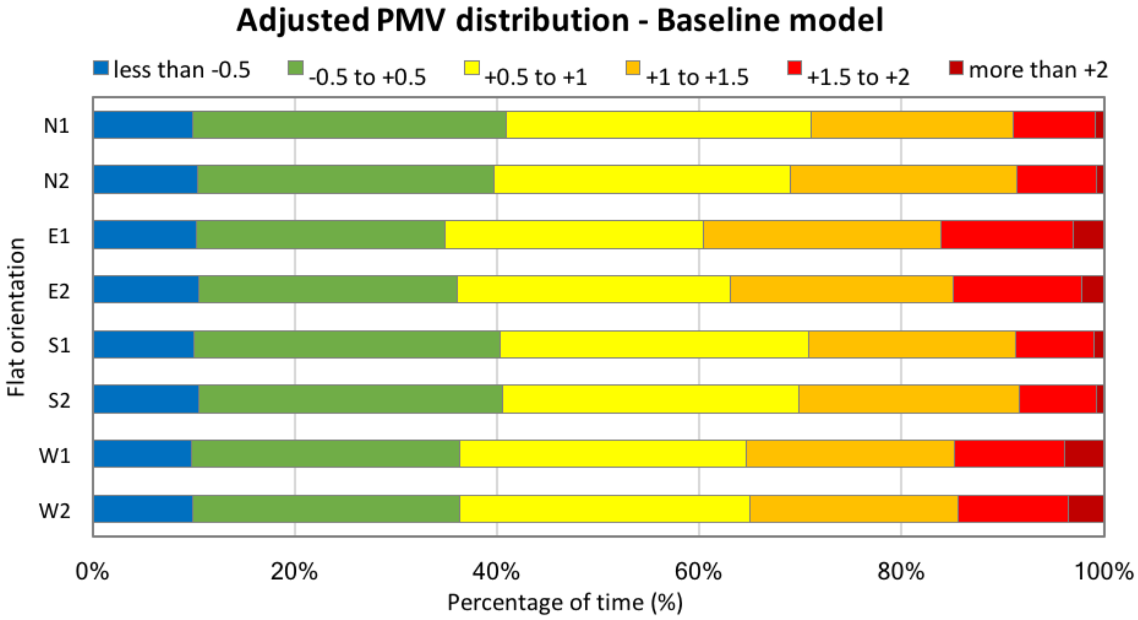


Figure 3. Adjusted PMV (e=0.7) distribution for flats facing different orientations in the baseline building model over June to August in the SRY.

3.2. Effects of wall U-value

The effects of altering the thickness of the concrete layer, and thus the U-value, of the external wall on the indoor thermal comfort are investigated for E flats and W flats (Figure 4). U-value is a measure of heat transfer rate and walls with a lower U-value are able to resist heat flow and provide better insulation for the indoor environment. By reducing the external wall U-value, the proportion of extreme discomfort hours (both very hot and cold) is reduced. The amount of time when occupants experience a PMV of more than +2 is nearly halved for both E flats and W flats. However, occupants do not enjoy more comfort hours (PMV -0.5 to +0.5). Instead, occupants feel warm to hot (PMV +0.5 to +1.5) for a longer duration of time in summer, with the proportion of time having a PMV of +1 to +1.5 reaching almost 30% in E flats for the U30 model.

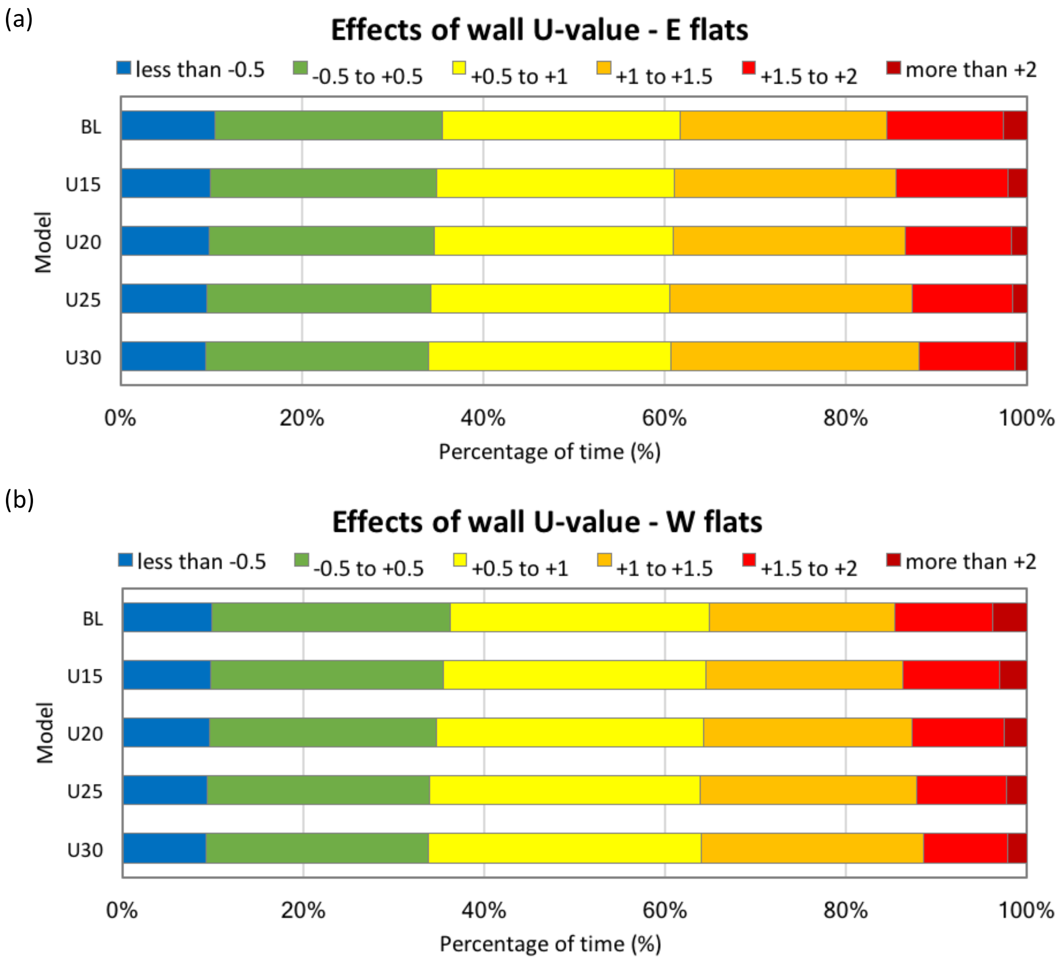


Figure 4. Effects of external wall U-value on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

The maximum and median T_{op} for E flats and W flats are plotted against wall U-values in Figure 5a. A positive and roughly linear relationship can be seen for maximum T_{op} and wall U-values, but median T_{op} remain largely constant for different wall U-values. Reducing the wall U-value is also able to narrow the T_{op} range experienced by building occupants during summer (Figure 5b). The effect is more prominent for W flats where the T_{op} range for model U30 is up to 10% smaller than the baseline scenario.

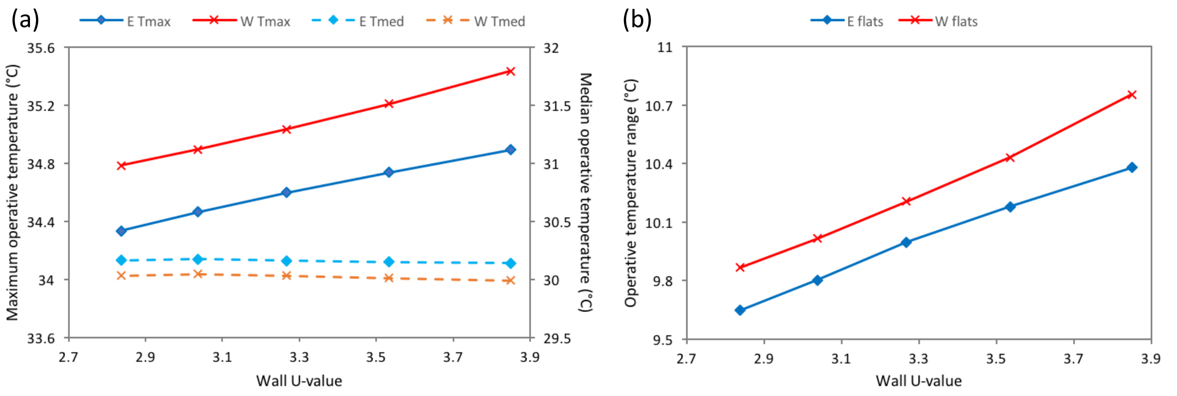
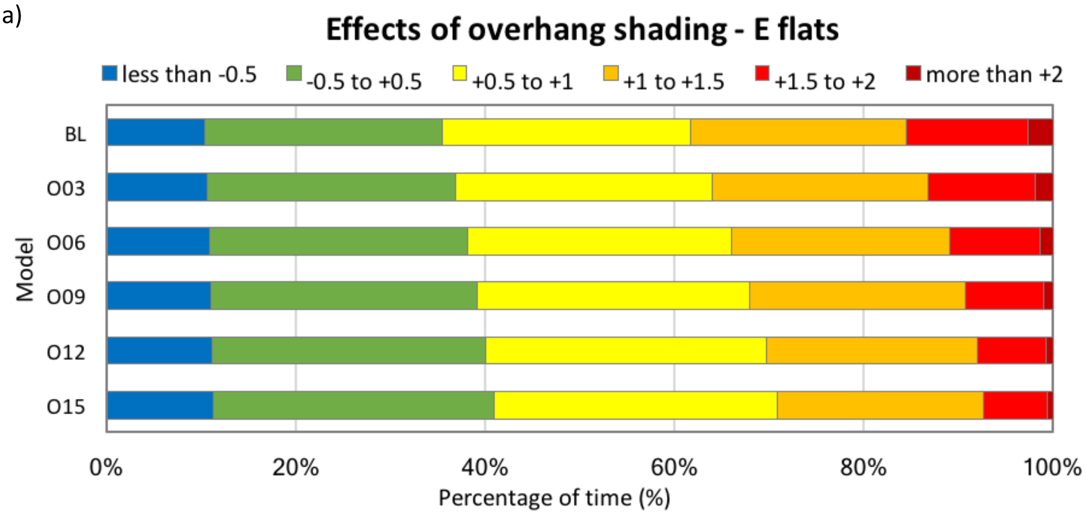


Figure 5. Relationships between external wall U-values and (a) maximum and median T_{op} and (b) T_{op} range for E flats and W flats.

3.3. Effects of window shading

A net cooling effect is achieved by providing overhang shading to windows. As seen in Figure 6, the thermal comfort of the indoor environment improves with increasing depth of the overhang shading for both E flats and W flats. Comparing the O15 model to the baseline scenario, the amount of time when occupants in free-running flats feel comfortable (PMV -0.5 to +0.5) increases by around 5% during the SRY. While occupants may feel cold for a similar amount of time with or without window shading, the proportion of hot to very hot hours (PMV +1.5 or above) is reduced significantly, with almost no time having a PMV of more than +2 for the O15 model.

(a)



(b)

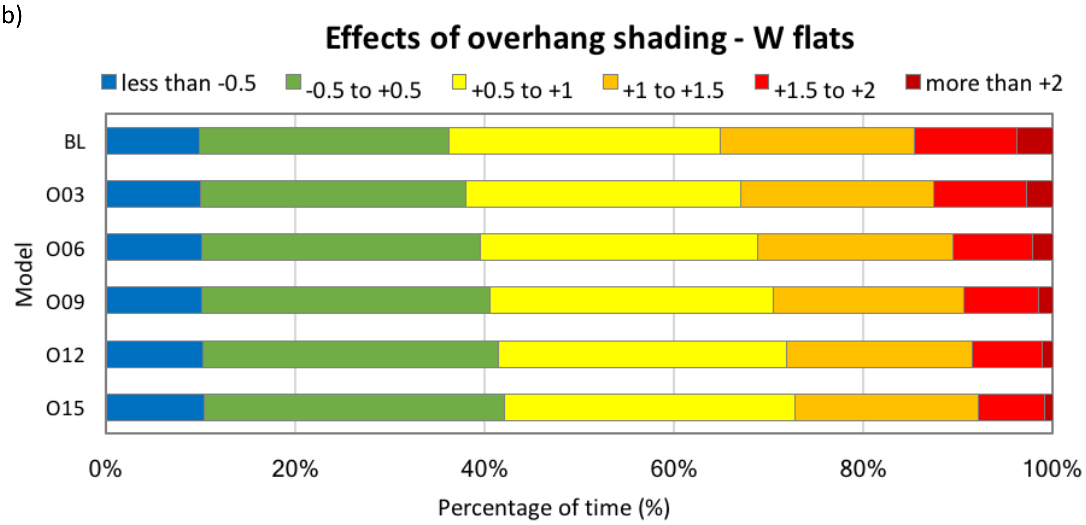


Figure 6. Effects of depth of window overhang shading on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

By looking at the maximum and median T_{op}, a non-linear and negative relationship is found between T_{op} and depths of overhang shading (Figure 7). The rate of T_{op} reduction gradually decreases as the length of overhang extends outwards from the external wall. Comparing the scales in Figures 7a and 7b, the magnitude of cooling by shading is found to be more prominent for the extremely hot conditions (represented by maximum T_{op}), especially for W flats. Also, consistent with previous findings by Huang et al. (2014), this design strategy also performs better for E flats and W flats than for N/S flats, as inferred from the steeper slopes of the curves in Figure 7.

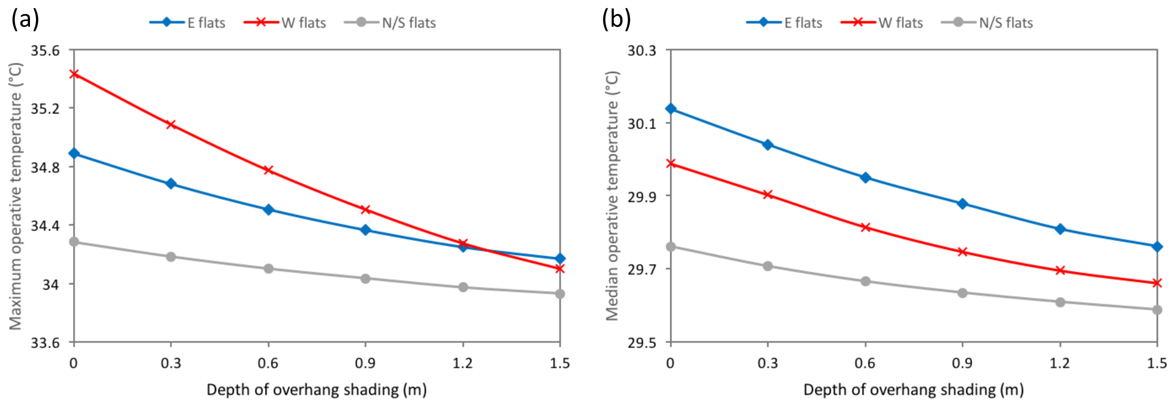


Figure 7. Relationships between depths of window overhang shading and (a) maximum T_{op} and (b) median T_{op} for E flats, W flats, and N/S flats.

3.4. Effects of window-to-wall ratio

Figure 8 shows the PMV distributions of models with different WWRs for E flats and W flats. The model having the minimum WWR of 0.033 performs the worst. Occupants may feel too warm (PMV higher than +0.5) for more than 80% of the summer time, with up to a third of which being PMV +1.5 or above for E flats. The amount of time within the comfort range (PMV -0.5 to +0.5) is only around 15%. When WWR is increased to 0.1, the indoor thermal conditions improve significantly. As WWR continues to increase, the amount of time within the comfort range also increases, but so does the proportion of very hot conditions with PMV +1.5 or above, except for when WWR increases to 0.4 in the BL model.

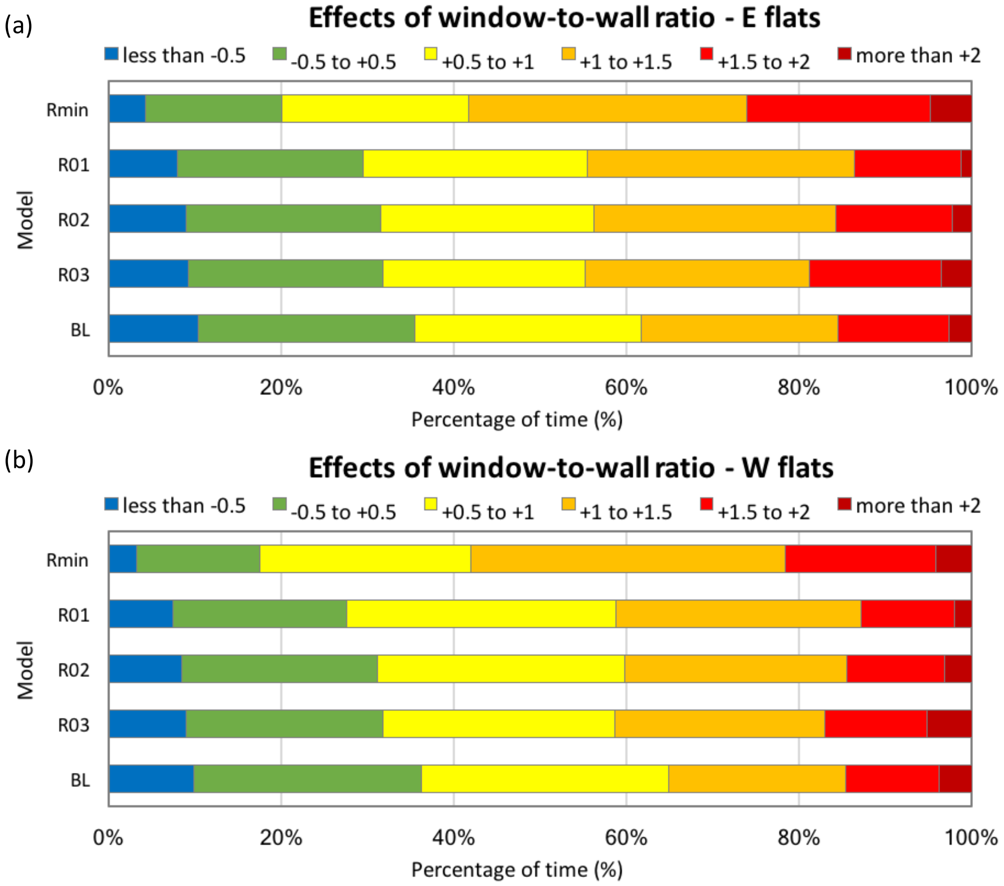


Figure 8. Effects of window-to-wall ratio on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

With reference to Figure 9a, to minimise discomfort due to extreme hotness, which can be represented by the maximum T_{op}, an optimum condition is found when WWR is 0.1. Maximum T_{op} then increases by around 0.5°C for each 0.1 increase in WWR. Median and minimum T_{op} display a different trend (Figure 9b). It is the hottest for the Rmin model, and both median and minimum T_{op} do not vary much for flats with WWR of 0.1 to 0.3. A slight drop in overall T_{op} is observed in flats of all orientations (N and S flats not shown) for the baseline model with a WWR of 0.4. This may be due to cross-ventilation made possible by extra windows, and will be further discussed in Section 4.3.

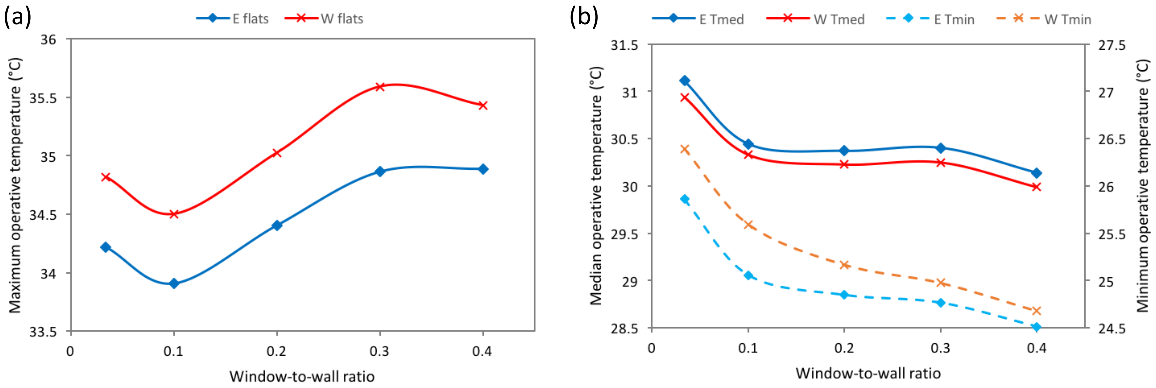


Figure 9. Relationships between window-to-wall ratios and (a) maximum T_{op} and (b) median and minimum T_{op} for E flats and W flats.

4. Discussion

4.1. Suitability of building insulation

Better insulated building envelopes are able to maintain a less variable indoor thermal environment. It is effective for narrowing the temperature range experienced by building occupants (Figure 5b). Reducing the external wall U-value reduces the duration of extreme discomfort indoors, both too cold and too hot (Figure 4). It can also save the energy required for mechanical cooling (Kwok et al., 2017). Building insulation is a crucial design element for buildings in temperate climates due to the wide annual temperature range and longer winter period (Yilmaz, 2007). London dwellings have typical wall U-values of 2.1 W/m^2K or even lower for newer or retrofitted buildings (Mavrogianni et al., 2012). However, in subtropical Hong Kong, results reveal potential overheating problems for flats with thicker walls and better insulation under free-running conditions in a near-extreme summer. Although extremely hot or cold conditions become less likely indoors, occupants may generally feel warm to hot for a greater proportion of time. Therefore, when applying insulation to high-rise residential buildings in hot and humid climates like in Hong Kong, it is important to strike a balance between building energy efficiency and the thermal comfort of those who may not be able to afford the high costs of air-conditioning.

4.2. Effective shading strategies

Providing overhang shading to windows results in a net improvement of the indoor thermal comfort of high-rise residential buildings in Hong Kong during near-extreme summer conditions (Figure 6). T_{op} in flats are effectively reduced as shading devices control the amount the direct solar radiation entering flats, especially for those facing the east or the west (Figure 7). Nevertheless, the flattening curves suggest that shading may no longer be effective after reaching a certain depth of overhang.

Another advantage of shading over other passive design strategies is its ease of implementation on existing buildings. They could be added to the standard PRH buildings, which are constructed from pre-moulded blocks, and could also be tailored for windows facing different orientations. Moreover, the use of other shading devices, such as vertical shading or side-fin projections, and egg-crate shading, could be explored to maximise the potential for temperature reduction (Al-Tamimi and Fadzil, 2011). Besides shading windows, shading external wall areas by erecting horizontal or vertical panels could also be an innovative and cost-effective solution to reduce heat uptake and transmittance through external walls into the interior of flats.

4.3. WWR requirement and cross-ventilation

According to the building regulations of Hong Kong, primary openings in a room should not be less than 1/16 of the floor area of the room (HKBD, 2016). This converts to a WWR of 0.033 for the building model used in this study. However, results present unreasonably hot indoor conditions for the model with minimum WWR. Occupants of all flats feel too warm (PMV higher than +0.5) for at least 80% of the time in a near-extreme summer (Figure 8, N and S flats not shown). An increase of the statutory minimum window area requirement could thus be recommended in light of these findings.

Cross-ventilation facilitates air movements across the indoor space and is particularly important for the thermal comfort of buildings in hot-humid climates (Givoni, 1994). Previous studies confirmed that better ventilation performance can be achieved by having two sets of openings placed opposite or perpendicular to each other (Gao and Lee, 2011). Unfortunately, most PRH flats in Hong Kong have windows positioned only on one side of the flat owing to the compact design and limited flat size. In the models of this study, windows were constructed based on the Concord type PRH layout with primary openings all facing the same orientation. For models with a higher WWR, secondary openings were added after the widths of primary openings have reached the full length of the primary façade (Figure 10). This potentially allows for cross-ventilation to occur, which is likely the reason for the improvement in indoor thermal comfort (Figure 8), as well as the slight drop in T_{op} observed (Figure 9). Therefore, in addition to the size of window openings, attention should also be given to how windows are positioned when optimising flats for thermal comfort under free-running conditions. To fully examine the effects of cross-ventilation, further studies using computational fluid dynamic (CFD) models would be required.

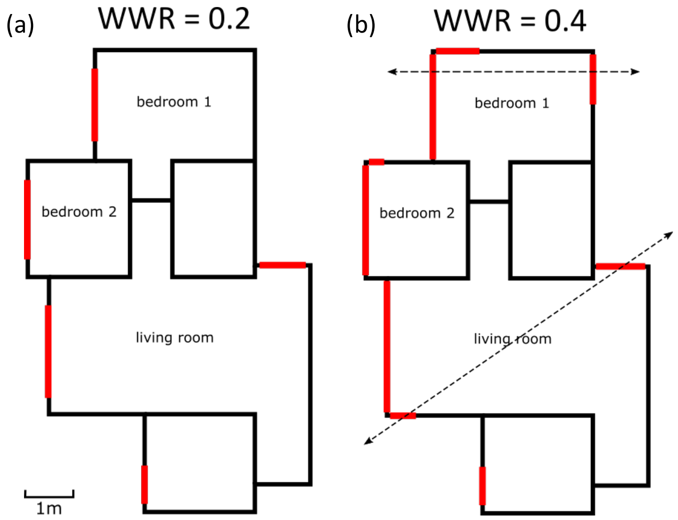


Figure 10. Floor layout and window positions (in red) of flat W1 in model (a) R02 and (b) BL. Arrows show potential cross-ventilation air movements.

4.4. Limitations of passive design strategies

Although careful design of the building envelope may improve the indoor thermal conditions of flats, none of the models examined were able to provide occupants with a thermally comfortable indoor environment (PMV -0.5 to +0.5) for more than 40% of the time during a near-extreme summer in Hong Kong. With rising outdoor temperatures, as well as more frequent heat wave events due to climate change, passive design alone is insufficient to help occupants in free-running buildings mitigate the indoor thermal discomfort. It is inevitable for occupants to adapt by using mechanical cooling such as fans and air-conditioning. Minimising cooling energy consumption while maximising indoor thermal comfort should be the goal for building optimisation research. This would require a tactful combination of improvement in building energy efficiency, HVAC system controls for mixed-mode ventilation, and most importantly, the design of the building itself.

5. Conclusion

In this study, the influence of three building envelope parameters, namely the wall U-value, the depth of window overhang shading, and the WWR, on the indoor thermal comfort of high-rise apartment flats under free-running conditions in subtropical Hong Kong has been investigated. Particular attention has been paid to take into account the more frequent near-extreme summer conditions due to climate change by employing the SRY weather data in building simulations. The varied effects for flats facing different orientations have also been evaluated.

Flats with lower wall U-values, and thus better insulation, have a less variable indoor thermal environment. Although extreme indoor conditions become less likely, occupants may feel generally warmer for a longer duration of time in summer. Overheating thus remain as a concern for well-insulated buildings in hot-humid climates. Window overhang shading induces a net improvement in the thermal comfort of flats, more notably for those facing the east or the west. It is also a cost-effective strategy which can be easily applied onto existing buildings. The minimum WWR required by current regulations results in unreasonably hot thermal conditions and should be revised accordingly. Besides identifying an optimal size for openings, they should also be placed to allow for cross-ventilation, which can further maximise the thermal comfort of flats under free-running conditions.

This study only serves to provide initial findings on how various building envelope parameters correlate independently with the indoor thermal comfort of high-rise residential buildings in subtropical climates. Further research is required to examine their combined effects and the optimisation of building performance using mixed-mode ventilation. The accuracy and reliability of simulation results could also be enhanced by validation with field measurements during heat wave episodes. Moreover, effective passive design strategies identified, such as shading and cross-ventilation, could be investigated in more detail by coupling thermal simulations with daylighting and CFD models. The combined findings are expected to contribute to the formulation of practical guidelines which could help engineers and architects design living spaces capable of providing thermal comfort and mitigating climate change.

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