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Investigating the energy saving potential of applying shading panels on opaque façades: A case study for residential buildings in Hong Kong

Sheng Liu[a,*], Yu Ting Kwok[a], Kevin Ka-Lun Lau[b,c,d], Pak Wai Chan[e], Edward Ng[a,b,c]

[a] School of Architecture, The Chinese University of Hong Kong, New Territories, Hong Kong
[b] Institute of Future Cities, The Chinese University of Hong Kong, New Territories, Hong Kong
[c] Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, New Territories, Hong Kong
[d] CUHK Jockey Club Institute of Ageing, The Chinese University of Hong Kong, New Territories, Hong Kong
[e] Hong Kong Observatory, Kowloon, Hong Kong

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ABSTRACT

In face of the warming climate, proper building designs are necessary to combat the ever-increasing energy demands, especially in high-density built environments. Shading is a common practice in subtropical cities owing to its effectiveness and feasibility. However, window shading alone is insufficient for achieving a satisfying energy performance and may often be a compromise to the visual comfort of occupants. In contrast, shading opaque façades has a great potential for energy saving with more design flexibility. This study proposes the adoption of shading devices on opaque façades and evaluates their energy saving potentials under near-extreme summer conditions by conducting building energy simulations. The length, the number, and the angle of tilt of shading panels are varied to explore the effects of different shading panel configurations for typical public rental housing buildings in Hong Kong. Optimal configurations that give maximum energy savings with the smallest total area of shading panels are found for different angles of tilt. Results show an energy saving potential up to 8.0% when shading panels are applied to flats with westward-facing façades. The energy saving coefficients within the optimal zones are also provided to guide the design of façade shading features in different urban contexts.

1. Introduction

To provide a thermally and environmentally comfortable indoor space for occupants, a considerable amount of energy is consumed in buildings, especially for their heating, ventilating and air-conditioning (HVAC) systems. Buildings currently account for 90% of the electricity consumption in Hong Kong and are the main targets for energy cuts in the energy saving plan of the government [1]. Hong Kong has a subtropical climate with hot and humid summers. Previous studies have shown that solar heat gain is the major heat source for high-rise buildings in Hong Kong and such buildings in a dense urban environment often suffer from overheating due to the intense solar radiation and high air temperature in summer [2,3]. Moreover, the situation is worsened as a result of intensified urban heat island (UHI) phenomenon due to climate change [4]. Therefore, occupants living in buildings with poor performance face increased risks of thermal discomfort, higher cooling energy costs, and even heat-related illnesses [5,6]. In Hong Kong, almost half of the total population live in public rental housing (PRH) [7], most of them are the elderly, physically disabled or financially less capable, making them all-the-more vulnerable under prolonged overheating conditions.

Various passive design strategies, such as the passive ventilation and cooling strategies, have been promoted to mitigate the worsening climate conditions [8]. Improving building envelopes, in aspects like envelope insulation, fenestration and façade design, also offers effective solutions [9,10]. However, it is not feasible to change the window-to-wall ratio or upgrade insulation layers of the building envelope by means of interior renovation when retrofitting the existing PRH buildings in Hong Kong, owing to the technical constraints of reconstruction, the consideration of cost efficiency, and the high occupancy rates of PRH buildings. On the other hand, the installation of external shading devices on the façade can be readily and uniformly implemented in buildings by the local government. Due to the ease of practice and relatively

* Corresponding author.
E-mail addresses: sheng.liu@link.cuhk.edu.hk (S. Liu), ytkwok@link.cuhk.edu.hk (Y.T. Kwok), kevinlau@cuhk.edu.hk (K.K.-L. Lau), pwchan@hko.gov.hk (P.W. Chan), edwardng@cuhk.edu.hk (E. Ng).

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Table 1
Summary of selected building simulation studies in the past decade on shading devices for locations with hot and humid climates in Asia.

Reference	Location	Building type	Shading strategy	Considerations
Fadzil and Sia, 2003 [27]	Penang (Malaysia)	Any building	Overhang with various shading depths (external)	Shading performance
Al-Tamimi and Fadzil, 2011 [28]	Penang (Malaysia)	Residential building	Overhang, horizontal and vertical louvers, egg-crate shading (external)	Thermal performance
Lim et al., 2012 [29]	Johor Bahru (Malaysia)	Office building	Overhang with vertical screen (external) and vertical blinds (internal)	Daylighting performance
Cheng et al., 2013 [30]	Taiwan	Any building	Overhang with various sizes (external)	Shading performance
Othman and Khalid, 2013 [31]	Petaling Jaya (Malaysia)	Office building	Venetian blinds and roller blinds (internal)	Daylighting performance
Chaiyapinunt and Khamporn, 2013 [32]	Bangkok (Thailand)	University building	Curved venetian blinds (internal)	Thermal performance
Yao, 2014 [33]	Ningbo (China)	Residential building	Movable solar shades (external)	Energy, indoor thermal, and visual performance
Wang et al., 2014 [34]	Guangzhou (China)	Commercial building	High and low level translucent blinds (internal)	Thermal and daylighting performance, cost analysis
Chan and Chow, 2014 [26]	Hong Kong, Beijing, Shanghai (China)	Office building	Self-shading by inverted pyramidal building	Thermal performance
Zhang et al., 2017 [24]	Hong Kong (China)	Temporary site office	Photovoltaic shading panels with various tilt angles (external)	Thermal, daylighting, and power generation performance
Xie et al., 2017 [25]	Hong Kong (China)	Public housing	Overhang with various lengths and tilt angles (external)	Energy performance and luminous comfort

low maintenance cost, shading devices are increasingly employed to reduce solar radiation through windows [11,12]. Different types of external shading devices include overhangs, side-fins, and external roller shades; the proper designs of which have been proved to be effective for reducing energy loads in air-conditioned spaces, especially in regions with hot climates [13]. It has also been found that fixed external shading devices generally have better performances and are more economical compared to internal or manually adjustable ones [14]. However, these external shading devices may not be universally applicable for high-rise buildings due to numerous physical constraints, such as the obstruction of views by window shading devices, the impacts on natural ventilation, and the requirements of indoor natural lighting. In particular, visual comfort and quality through the exterior windows are important factors of occupant satisfaction and health [15,16]. Residents of high-rise buildings in Hong Kong prefer having their windows, especially those with a view of the sea or mountain, unobstructed by shading devices. This leads to a trade-off between thermal comfort and visual quality for the occupants. Consequently, despite of its proven effectiveness, window shading has not been extensively applied on residential buildings in Hong Kong and more energy demand is expected to maintain indoor thermal comfort in the future. Even if applied, window shading alone may be insufficient to achieve a satisfying energy performance when large areas of eastward- and westward-facing walls are exposed to prolonged solar beam radiation. Therefore, alternative solutions with optimized shading configurations are required [17].

Previous studies on shading devices for buildings covered a wide range of shading strategies for transparent façades (see review [18]). A brief summary of relevant simulation studies on building shading conducted in the past decade for Asian cities with hot and humid climates comparable to that in Hong Kong are presented in Table 1. Much research with considerations on the thermal and daylighting performances of common windows shading devices like external overhangs, louvers, and internal blinds has been carried out, but there is generally limited research investigating the potential of applying shading on opaque building façades. In recent years, the use of opaque ventilated façades (OVF) is gaining popularity in Southern European countries, e.g., parts of Italy and Spain with Mediterranean summer weather conditions [19,20]. OVF can effectively reduce the summer cooling loads, because the natural stack effect inside the air duct of ventilated facades can promote air flow and the convective heat transfer; on the other hand, part of solar radiation irradiated on façades is reflected by the external skin [21–23]. Nonetheless, the applicability of OVF in countries with different climates is uncertain as building envelope designs need to be adapted the corresponding urban contexts and the relevant local regulations and practices. Taking Hong Kong as an example, recent simulation studies evaluated the thermal performances of buildings with specific configurations of shading devices on façades facing different orientations [24–26]. Such detailed and quantitative results bear significant practical implications for the design of energy-efficient buildings.

Tall buildings in Hong Kong have large vertical surface areas and thus shading the opaque building façades, i.e. the non-window areas of external walls, has a great potential for heat gain reduction due to its design flexibility without constraints in visual comfort. This study therefore proposes the innovative design of shading panels on the opaque façades of PRH buildings in Hong Kong.

Out of the above considerations, this study aims to

1. Investigate the energy saving potentials of adding shading devices on opaque building façades facing different orientations under near-extreme summer conditions in Hong Kong;
2. Explore the effects on energy demand reduction when three design parameters (the length, the number, and the angle of tilt from the external wall) of the shading panels are varied; and
3. Identify the optimal configurations of façade shading devices to achieve the maximum cooling load reduction using the least amount of materials.

2. Methodology

2.1. Simulation model and settings

Building simulations were set up with the DesignBuilder V5 software, in which building performance data were generated using the state-of-the-art dynamic EnergyPlus V8.5 simulation engine, developed by the US Department of Energy [35]. This

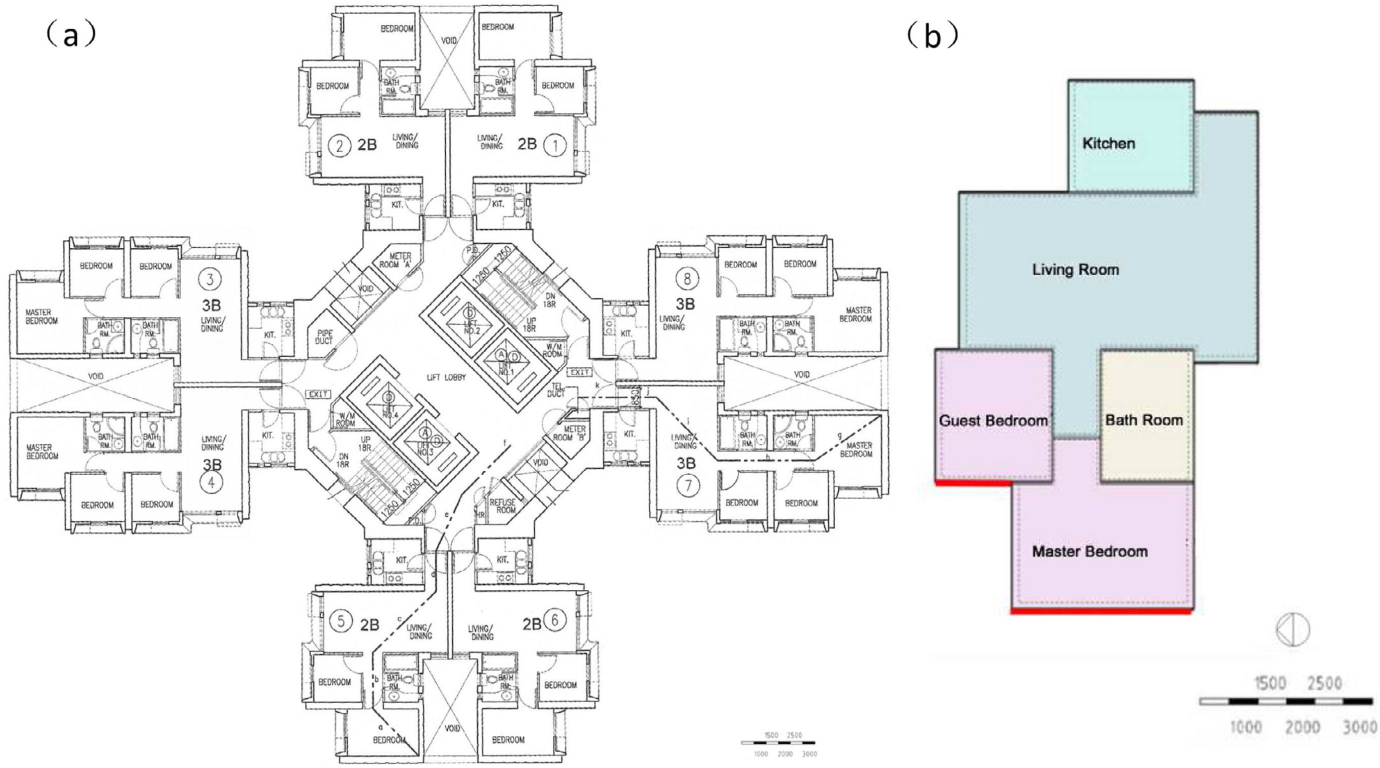

Fig. 1. (a) Floor plan of Concord type PRH. (b) Simplified floor plan of a flat with two bedrooms. Red bold lines show the westward-facing façades of this flat where shading panels will be added. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

software has been selected by ASHRAE as the proper method for the estimation of buildings' energy performances [36]. The hourly heat gain components, including heat conduction and solar radiation through the building envelope, can be computed by EnergyPlus. In addition, this software has been validated for simulating the detailed energy balances between the façade and shading devices [37].

The Concord type PRH building (Fig. 1a) has been chosen as the subject for case study. It represents the typical form of residential buildings in Hong Kong and is prevalent among the latest PRH estates as well as those now being constructed [38]. As this study only focuses on investigating the energy saving potential of shading panels, a simplified model – a three-storey residential building with a square floor plan – was employed in the parametric study. The optimized configurations for the shading panels were then applied to the flats with westward-facing opaque façades on the Concord type PRH building (Fig. 1b). To reduce the computational cost, only the rooms with shading added in the middle three floors were included in thermal calculations, as shown in Fig. 2. The building physical parameters are summarized in Table 2. More details on the model settings and information on PRH buildings and construction materials can be found in the previous simulation study by Kwok et al. [39]. The cooling load from April to September of the mid-floor flat was simulated for analyzing the summer cooling energy demand. To consider the real occupant behavior which involves hybrid ventilation of natural ventilation and mechanical cooling, HVAC system is set to mixed mode, with a cooling setpoint temperature of 25°C to prevent simultaneous natural ventilation and cooling system operation.

In order to consider reflected diffuse solar radiation from both the shading and ground surfaces, the reflection and full exterior solar distribution were considered in simulations. In doing so, shadow patterns on exterior façade surfaces caused by detached shading, overhangs, and all shading component blocks were computed [40]. Solar radiation irradiating on building envelope includes beam radiation, sky diffuse radiation, ground reflection radiation, diffuse radiation reflected from surrounding buildings, and longwave radiation. In EnergyPlus [41], the calculation of total solar radiation incident on exterior surfaces (Q_{so}) combines both the direct and diffuse solar radiation, and is given by:

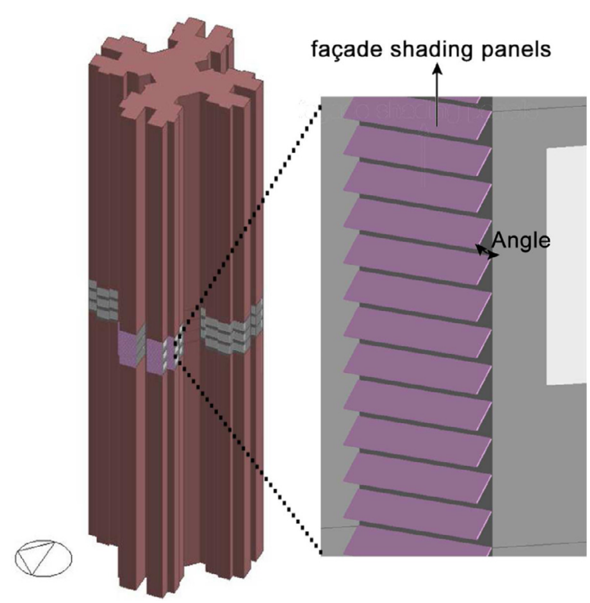

Fig. 2. The simulation model with shading panels applied on the opaque façades of a Concord type PRH building.

$$Q_{so} = \alpha \cdot \left(I_b \cdot \cos\theta \cdot \frac{S_s}{S} + I_s \cdot F_{ss} + I_g \cdot F_{sg} \right) \tag{1}$$

Table 2
Building physical parameters for the models used in the simulations.

	Building type	
	Concord type PRH	Simplified model
Total occupied floor area (m^2)	325.1	36.0
Cooled area (i.e. living room, bedroom) (m^2)	256.8	36.0
U-value of external wall ($W\ m^{-2}\ K^{-1}$)	2.75	
Window to external wall ratio	0.148	
Floor height (m)	2.75	
U-value of roof ($W\ m^{-2}\ K^{-1}$)	0.58	
U-value of internal partition ($W\ m^{-2}\ K^{-1}$)	2.86	
U-value of floor slab ($W\ m^{-2}\ K^{-1}$)	2.48	
U-value of Glazing ($W\ m^{-2}\ K^{-1}$)	5.75	

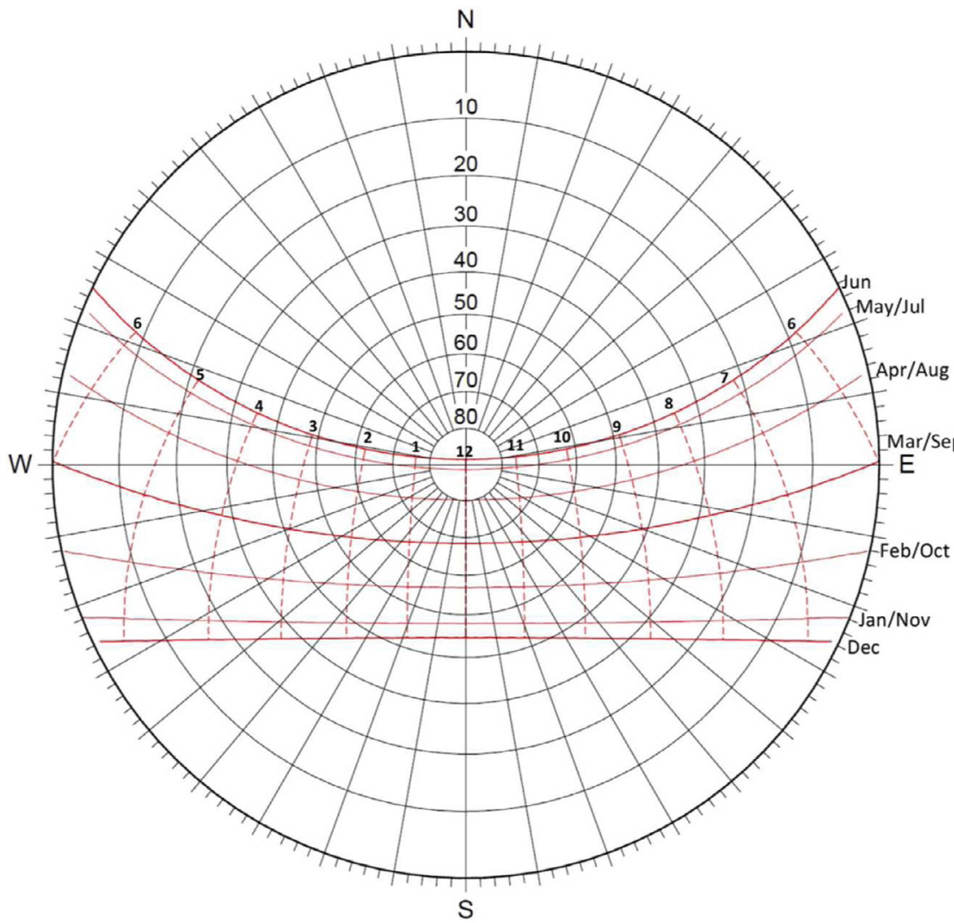

Fig. 3. Stereographic sun path diagram for Hong Kong (22°19′N/114°10′E) [26].

Where α is the solar absorptance of the surface, θ is the angle of incidence of the sun's rays, S is the total surface, S_s is the sunlit area of surface, I_b is the intensity of beam direct radiation, I_s is intensity of sky diffuse radiation, I_g is the intensity of ground reflected diffuse radiation, F_{ss} is the angle factor between the surface and the sky, and F_{sg} is the angle factor between the surface and the ground.

2.2. Weather data

Hong Kong is located in the subtropical region (22°19′N/114°10′E) with a mild climate in winter and a long and very hot humid summer. The stereographic sun path diagram in Hong Kong is presented in Fig. 3. Near-extreme summer conditions were considered in this study since they have occurred more frequently in recent years and are expected to be more frequent and intense in the future. In this study, Summer Reference Year (SRY) meteorological dataset was used as input weather data in EnergyPlus to represent near-extreme summer conditions. SRY was proposed by Jentsch et al. [42] and has been proven capable of applying to any locations since it is developed based on site-specific data. Such a near-extreme meteorological dataset is particularly applicable to naturally ventilated and mixed-mode buildings. The derivation of the SRY dataset for Hong Kong is detailed by Lau et al. [43]. By applying adjustments to the Test Reference Year (TRY), it considers near-extreme conditions during the extended summer months from April to September, based on the ground-level meteorological observations recorded by the Hong Kong Observatory (HKO) between 1981 and 2010.

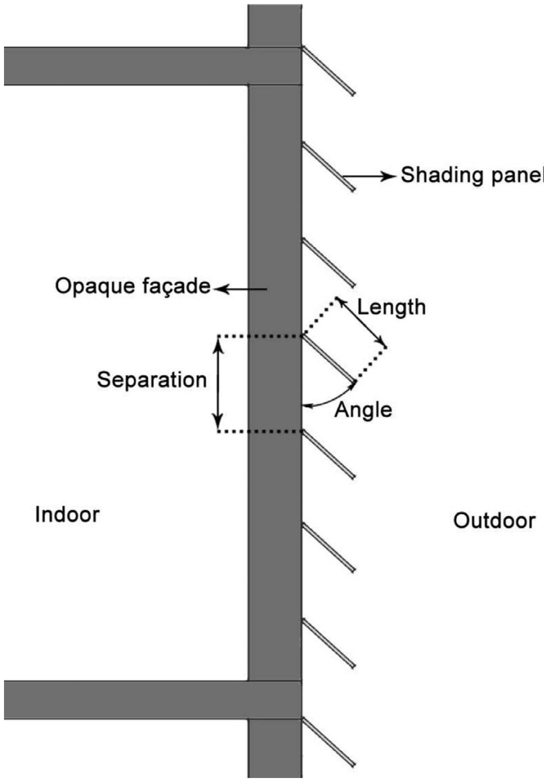

Fig. 4. Input parameters of shading panels for the simulation.

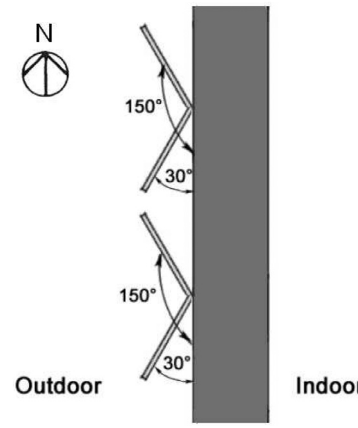

Fig. 5. Illustration of the difference between vertical shading panels at 30° and 150°.

2.3. Shading panel types and parameters

In this study, two types of façade shading devices, i.e., vertical and horizontal shading panels, were applied separately on the external opaque walls. According to the *Practice Note for Authorized Persons APP-156* of Hong Kong Buildings Department [44], external shading should extend no longer than 750 mm from the wall in order not to cause obstruction and danger. Therefore, the maximum panel length used in this study was set to 700 mm. Shading panels were constructed as component blocks in the model; the default material was set to concrete with a thickness of 10 mm and solar absorptance of 0.6.

As previously described, this study assumes that view obstruction is not a concern for the opaque building façades. Thus, the angle between shading panels and the external wall could be varied freely. Three parameters as shown in Fig. 4, i.e. the angle of tilt, the length, and the number of shading panels, were selected for a detailed parametric analysis. An angle of 90° means that the shading panels are perpendicular to the façade, while 0° represents panels parallel to the façade. It is well noted that rotating the direction of a perpendicular shading panel (with an angle of tilt = 90°) in vertical type have two options: to the north or to the south. Under the assumption that rotating shading panels to the south direction makes an acute angle, rotating them to the north direction forms an obtuse angle, but both of them result in an angle of the same size between the panel and the wall, as shown in Fig. 5.

The variables investigated are as follows (Table 3): the angles of tilt are namely 150°, 120°, 90°, 60°, and 30°; the length of shading panels varies with a range between 0.1 m and 0.7 m; the number of shading panels per wall surface varies for the vertical and horizontal shading panels due to the difference in flat height and width, but the separation for both panel types decreases from 0.92 m to 0.12 m. By adding component blocks to the base model, the cooling loads from April to September were simulated by changing the captioned parameters of the shading panels. Energy savings are presented as a percentage reduction from the base model without any shading.

3. Results and discussion

3.1. Energy savings by shading opaque building façades in different orientations

Effects of opaque façade shading on energy saving have been analyzed in the preliminary test, so as to explore the sensitivity of building energy efficiency to shaded façades with different orientations. These simulations were performed by adding identical shading panels (with a length of 0.55 m and a separation of 0.55 m) for both horizontal (imitating overhang projection) and vertical (imitating side-fin projection) shading types, perpendicularly (at an angle of 90°) on façades facing eight orientations (S, SW, W, NW, N, NE, E, SE). With reference to Fig. 6, the horizontal and vertical shading panels have similar effects on energy saving for façades facing all orientations, except for those facing the west and the east, where horizontal shading panels can achieve energy savings up to 5.6%, but the effects of vertical shading panels are limited to around 2.5% only.

Overall results show that shading opaque façades in the west and the southwest orientations have the most potential for energy saving for both horizontal and vertical shading types. The relatively poor performance of the perpendicular vertical shading panels

Table 3
Details of the three shading panel parameters investigated.

Shading type	Variables of parameters		
	Angle	Number of panels (Separation/m)	Length of panels/m
Vertical	150°, 120°, 90°, 60°, 30°	7(0.92), 13(0.46), 26(0.23), 52(0.12)	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7
Horizontal	90°, 60°, 30°	3(0.92), 6(0.46), 12(0.23), 24(0.12)	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7

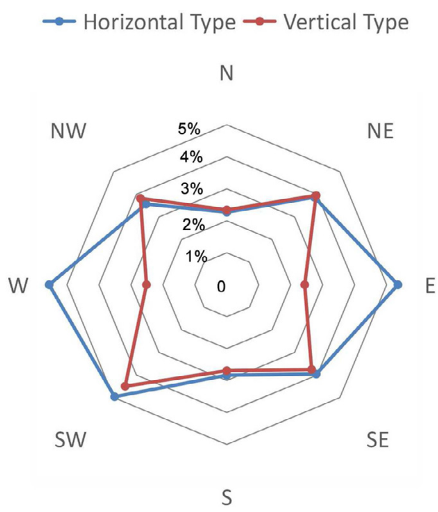

Fig. 6. Energy saving rate of typical shading panels on façade with different orientation.

facing the west and the east can be explained by the fact that direct solar radiation is almost perpendicular to the walls but parallel to the vertical shading panels in these directions. As a result, the vertical shading panels at 90° from the wall are not able to effectively block incident radiation for façades. However, they can be optimized by modifying other parameters (e.g. the angle of tilt or length of shading panels) to achieve a better building energy performance. To better illustrate the effects of different shading panel parameters on energy savings, the most sensitive orientation was selected for subsequent parametric and optimization analyses. Therefore, shading panels were only added to flats with westward-facing opaque façades for the rest of this study.

3.2. Parametric analysis of shading panels on opaque building façades

3.2.1. Horizontal shading panels

The variations of energy saving from April to September using horizontal shading panels with different parametric settings (for the angle, length, and number) are plotted in Fig. 7. Graphs on the left and right columns show separately the effect of the length of panels, and the effect of the number of panels.

For the base case at an angle of 90° (Fig. 7a and b), the amount of energy saved generally increases with the number and length of shading panels. However, the stepwise increment in energy saving gradually decreases as the number and length of shading panels increases. Similar trends are found when the angle between the wall and the shading reduces to 60° and 30°. At an angle of 60°, the energy saving displays a slowed growth when the number and length of panels exceeds 6 and 0.4 m and 6, respectively. When

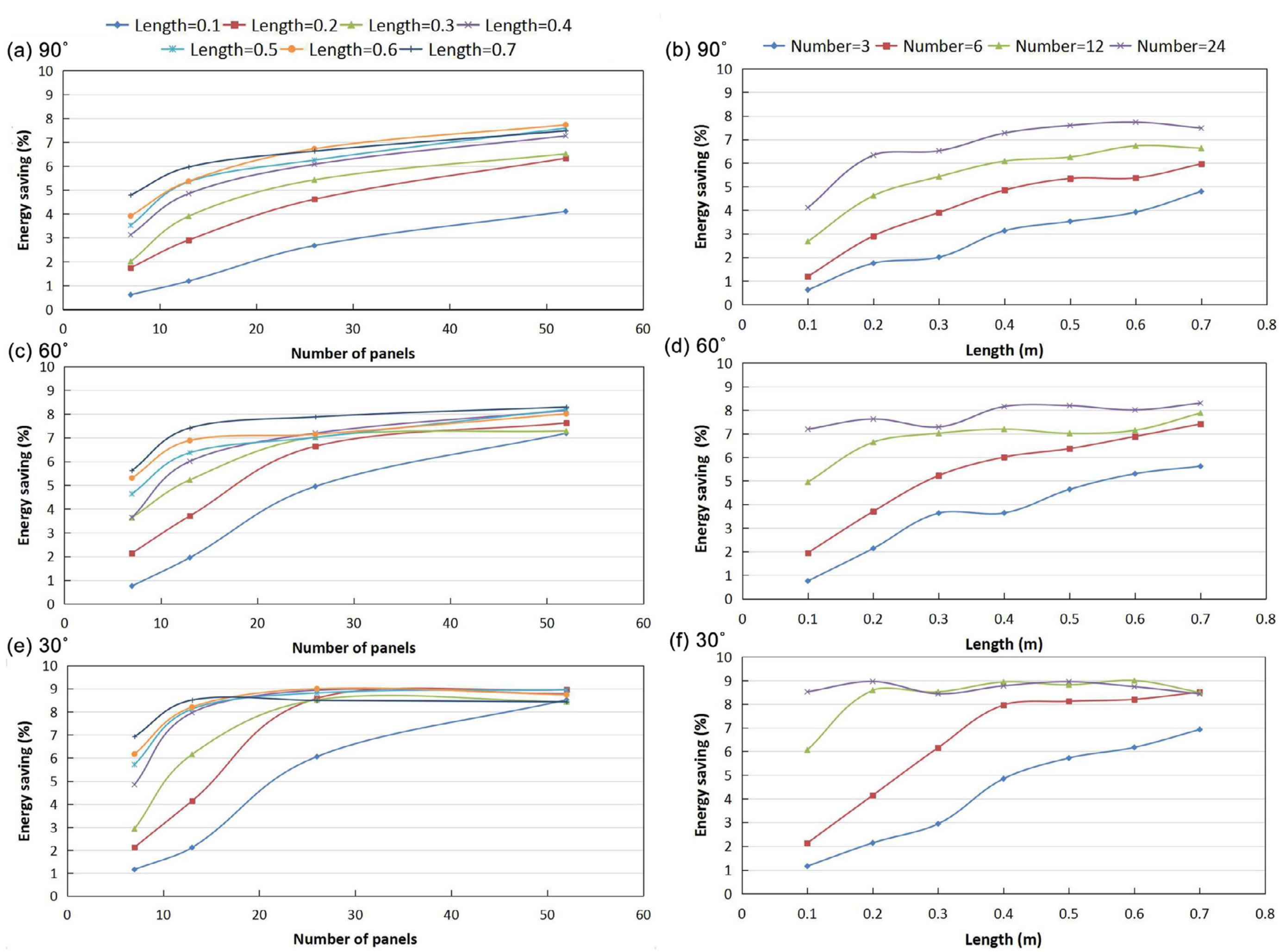

Fig. 7. Relationships between the energy saving rate and the number and the length of horizontal shading panels at an angle of (a, b) 90°, (c, d) 60°, and (e, f) 30°, respectively.

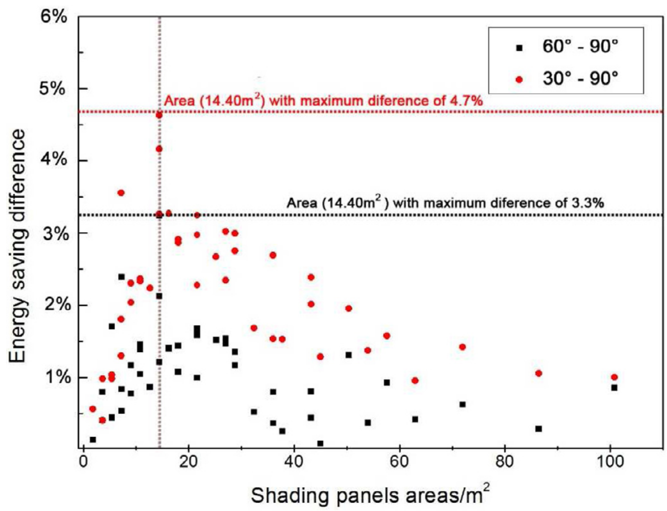

Fig. 8. Comparison of energy saving difference with shading panels areas for horizontal shading panels. Black squares are the differences between panels at angles of 90° and 60°, red dots are the differences between panels at angles of 90° and 30°.

the angle is further reduced to 30°, there is an obvious plateauing trend in energy saving at 9% for most combinations of the number and length of shading panels, except for the shortest panels with a length of 0.1 m, which continue to show a roughly linear increase in energy saving as the number of panels increases. This suggests that the maximum energy saving can often be achieved using a lower number and shorter length of shading panels, which is the reason why optimization of shading panel configurations is necessary.

When the results for the three different angles of tilt are compared, a largely similar trend can be observed, but the plateau in energy saving is reached at a lower number and a shorter length of shading panels when the angle of tilt becomes smaller. In other words, at a smaller angle of tilt from the external wall, the shading panels can achieve greater energy efficiency using the same number and length of shading panels. This change is due to the effective blockage of solar radiation incident on the façade with a lower solar altitude, especially in the early morning or the late afternoon, when horizontal shading panels are tilted towards the wall. Furthermore, by comparing the differences in energy saving rates between horizontal shading panels at the angle of 60° and 90°, and 30° and 90°, Fig. 8 demonstrates that the maximum differences in energy saving are 3.3% and 4.7%, respectively. Interestingly, the maximum differences occur coincidently at a shading panel area of 14.4 m^2 (calculated by number of shading panels × length of shading panels × width of the façade). It indicates the most sensitive response in energy saving when the angle of tilt is changed for horizontal shading panels with this particular value of panel area.

It should also be noted that the increase of shading panel length may cause no further energy reduction, and even a penalty effect, when the number of panels is more than 12 (separation is less than 0.23 m) at an angle of 30° (Fig. 7f). When shading with long and dense panels, most of the beam radiation irradiating on the façade can be blocked, leaving only diffuse radiation to reach the building wall surfaces [45]. In EnergyPlus, the solar radiation irradiating on the surface of panels from the ground reflected radiation and sky diffuse radiation have been well considered, as described by Eq. (1). Therefore, the penalty effect in energy saving is caused by the increase in diffuse solar radiation irradiating on the westward-facing building façade from the compact shading panels, especially during the afternoon, when the shaded areas of the façade reach a maximum.

3.2.2. Vertical shading panels

For vertical shading panels, cooling energy savings are plotted against the variations of the number and length of panels in Fig. 9. For the base case with shading panels positioned perpendicularly to the façade, a roughly linear positive relationship can be seen between energy saving and the number and length of panels (Fig. 9a and b). By decreasing the angle between shading panels and the façade to 60° and 30°, the curves of energy saving asymptotically approached obvious maxima (8.7% and 9.0%) as both the number and the length of shading panels increase. For instance, at an angle of 30° (Fig. 9e and f), compact vertical shading panels (with 13 panels or more and a length longer than 0.3 m) do not cause any further reduction in cooling energy when maximum possible area of the façade has been shaded. Compared with the same combination of the length and the number of vertical shading panels, the energy saving potentials varied significantly for different angles, e.g., using 13 panels with lengths of 0.7 m, the absolute amount of energy saved for shading panels at an angle of 30° can be up to 451 kWh, whereas it is only 162 kWh at an angle of 90°.

Meanwhile, comparing the differences in energy saving rates achievable by vertical shading panels of the same total area (calculated by number of shading panels × length of shading panels × height of the façade) at different angles of tilt, Fig. 10a shows a maximum difference of 4.3% between panels at 60° and 90° and a maximum difference of 6.2% between panels at 30° and 90°. This reveals the potential to achieve a significant increase in energy saving just by changing the angle between the wall and vertical shading panels. When the two types of shading panels are compared (Figs. 8 and 10a), effects due to changes in the angle are much more sensitive for vertical shading panels. However, the corresponding shading panel areas (27.23 m^2 for panels at 60° and 90°, 21.45 m^2 for panels at 30° and 90°) where the maximum differences occur for vertical shading panels are also larger.

The comparison of energy saving between the angles of tilt of 120° and 60°, and 150° and 30° are plotted against shading panel areas in Fig. 10b. Shading panels with an angle of tilt of 60° provide better shading and the mean cooling load reduction is 18.07 kWh higher than those with an angle of tilt of 120°. This difference can be explained by the sun path diagram in Hong Kong shown in Fig. 3. As Hong Kong is located in the northern hemisphere (latitude 22°19′ N), for a westward-facing façade, from 12:00 noon to 6:00 pm, the direction of solar beam radiation changes from the west with an azimuth angle of 270° to the northwest with a maximum azimuth angle of 295.4° during March to September. For the summer period simulated in this study (from April to September), the shading panels with an angle of 60° can effectively block most of the beam radiation on westward-facing façade in the late afternoon. Whereas if the vertical panels rotate to north direction to form an angle of tilt of 120°, the façade will be directly irradiated by beam radiation in during most of the summer afternoon times. However, there is not a noticeable change between the shading panels with angles of tilt of 30° and 150°, as both orientations of the shading panels are titled close enough to the wall, such that the façade can be sufficiently shaded from beam radiation from the west and northwest.

3.3. Optimal configurations of shading panels

This section explores the optimal configurations of shading devices on opaque façades for the best cost-effectiveness, i.e. the greatest energy saving with the smallest total area of shading panels (as a proxy for the cost of construction materials). By increasing of the number of parameter variations, more design scenarios can be obtained for the fitted curve. However, there needs to be a balance between the precision and the number of simulations to be performed due to the cost of time and resources [46].

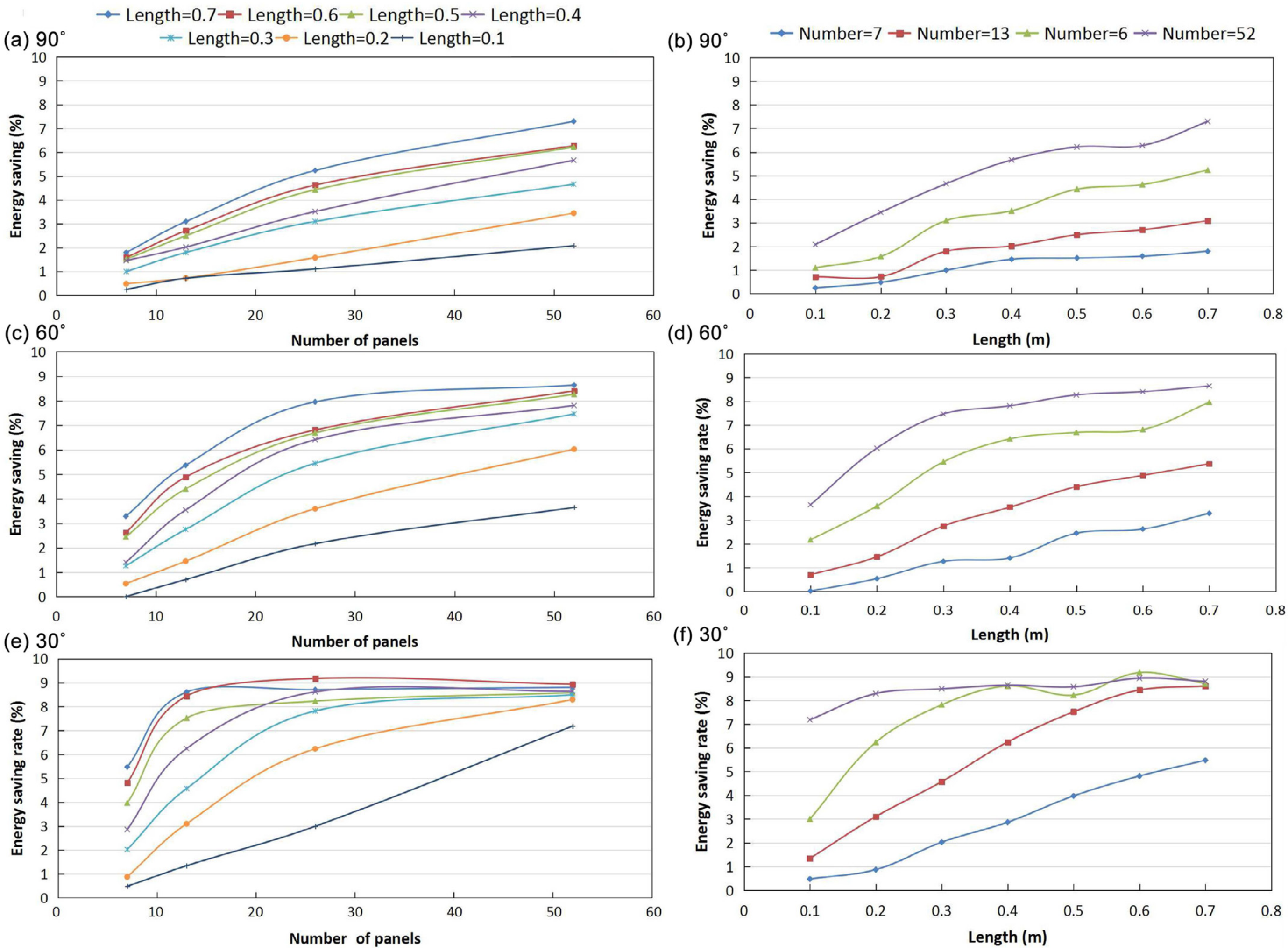

Fig. 9. Relationships between the energy saving rate and the number and the length of vertical shading panels at an angle of (a, b) 90°, (c, d) 60°, and (e, f) 30°, respectively.

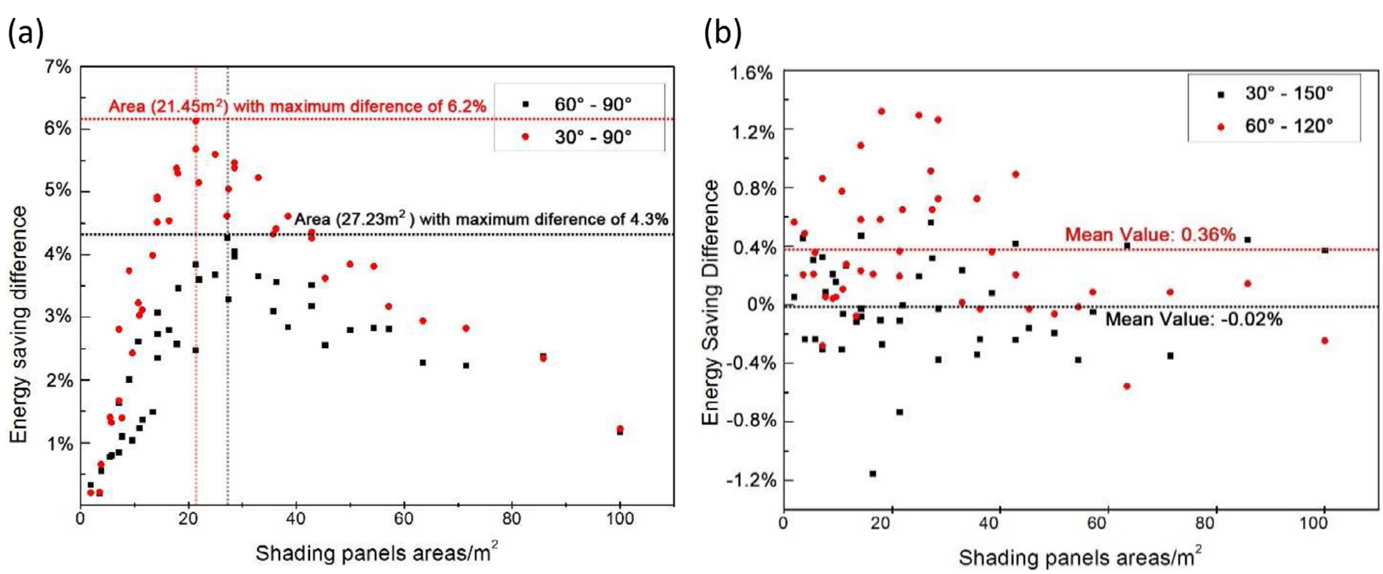

Fig. 10. Comparison of energy saving difference with shading panels areas for vertical shading panels between panels at angles of (a) 90° and 60° (black squares), 90° and 30° (red dots), and (b) 150° and 30° (black squares), 120° and 60° (red dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

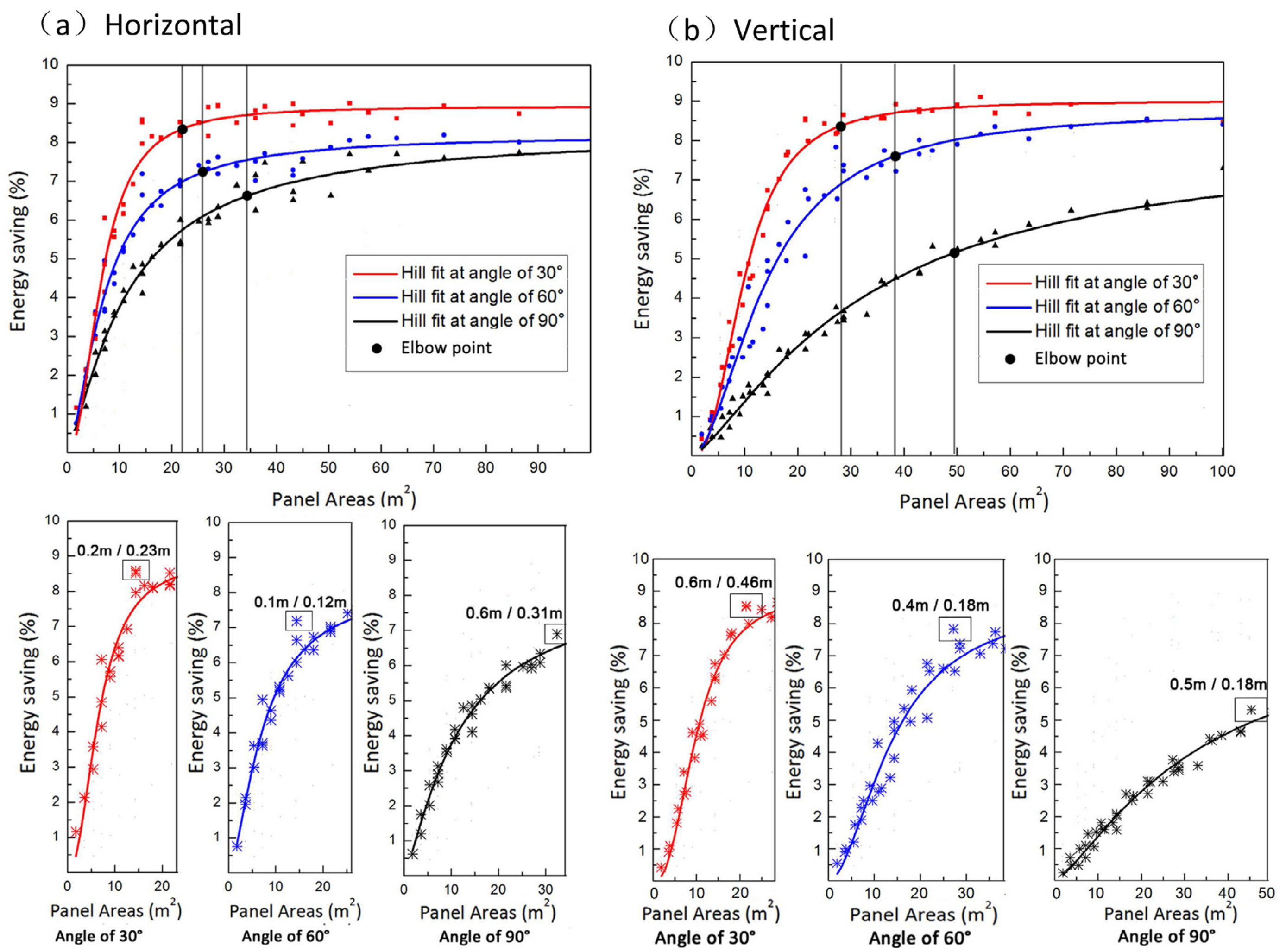

Fig. 11. Scatter plots (dots) and hill regressions (curves) for (a) horizontal and (b) vertical shading panels. The optimal zones are enlarged beneath the main plots and the black squares indicate the optimal configurations.

Compared to the previous parametric analysis, two more variables for the number (separation) of shading panels, namely 9 (0.31 m) and 15 (0.18 m) for horizontal type, 20 (0.31 m) and 33 (0.18 m) for vertical type, were added to increase the probability of scenarios located in the optimal zone, where energy saving have the most sensitive response to the total areas of shading panels.

Clearly, the scatter plots present a non-linear relationship between the total area of shading panels and energy saving, but dots for the three different angles all appear to reach a maximum value for energy saving as the panel area increases. Hill plots are often used to describe non-linear relationships with a certain saturation value and the characteristically sigmoidal curves. The Hill coefficient provides a way to quantify the shape of response between inputs and outputs, and the maximum response can be generated by the Hill equation [47]. Observed from the scatter plots (Fig. 11), the potential energy saving approaches an asymptotic maximum value when the total area of shading panels continues to increase. Such an input-output relationship can be examined by fitting with the Hill equation [48]:

$$y = V_{\max}\left(\frac{x^n}{k^n + x^n}\right) \tag{2}$$

Where the response of the dependent variable y (energy saving) saturates asymptotically at V_{max} for increasing levels of the independent input variable x (total area of shading panels), the shape of response is determined by the Hill coefficient n, and half of the maximal response is $x = k$. In this case, the $V_{\max}$ represents the maximum energy saving potential for shading panels at different angles, n represents the general response of energy efficiency to the shading panel area, and k represents the area of shading panels required for achieving half of the maximum energy saving at different angles. In order to illustrate the sensitivity of the increase of energy saving with respect to the change in total area of shading panels, the following equation can be derived:

$$y' = V_{\max}\frac{nx^{n-1} \cdot k^n}{(k^n + x^n)^2} \tag{3}$$

Based on the 126 cases (3 angles × 7 lengths × 6 separations) for each of the two shading types (horizontal and vertical), the relationships between energy saving and the total areas of shading panels with the different angle are demonstrated in the scatter plots and the fitted curves in Figs. 11 and 12. The energy saving-shading areas relation from the building simulations fit reasonably well to the Hill equation, with adjusted R-square values for all fitted curves above 0.96. The corresponding Hill equation variables and coefficients are listed in detail in Table 4.

For both horizontal and vertical shading panels, shading panels with a smaller angle of tilt can achieve a higher maximum energy saving (about 9.0% at the angle of 30°). This, again, can be explained by the Eq. (1). When direct beam radiation on the façade

Table 4
Hill equation variables and coefficients for horizontal and vertical shading panels at different tilt angles.

Shading type	Angle	Maximum energy saving ($=V_{max}$)/%	Half maximal response area ($=k$)	Response Hill coefficient (n)	Adjusted R^2	The optimal configurations (Length/Separation)	Area of panels at elbow point (slope = 0.05)/m
Horizontal	90°	8.282	11.579	1.275	0.975	600 mm/310 mm	34.030
	60°	8.187	7.206	1.585	0.969	100 mm/120 mm	26.247
	30°	8.930	6.591	2.221	0.962	200 mm/230 mm	22.622
Vertical	90°	8.038	32.116	1.342	0.986	500 mm/180 mm	49.597
	60°	8.787	13.952	1.849	0.967	300 mm/180 mm	38.034
	30°	9.003	9.905	2.485	0.982	600 mm/460 mm	28.389

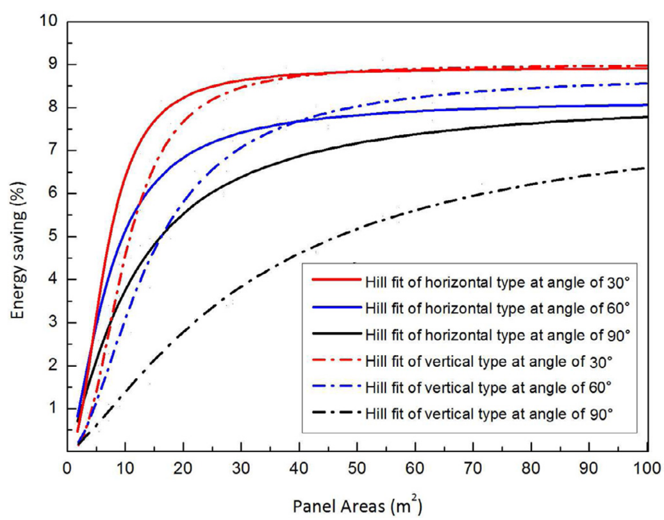

Fig. 12. Comparison of hill fitted lines between horizontal and vertical shading panels at different angles.

is fully/mostly blocked by shading panels, building envelope heat gain mainly comes from reflected diffuse radiation. Shading panels at a larger angle (e.g. at 90°) have a larger sunlit surface (S_s) exposed to solar beam radiation with a lower angle of incidence of the sun's rays (θ), leading to more reflected diffuse radiation from shading panels irradiated on the façade. In addition, some direct beam radiation from the low angle sun in the late afternoon may reach can reach the westward-facing façade with shading panels at the angle of 90°. It can also be observed that shading panels at a lower angle generally have a better response for energy efficiency. Moreover, for shading panels with the same angle from the wall, all the response coefficients n of those in vertical type are greater than those in horizontal type.

An elbow point of each curve, defined as the point with a local slope of 0.05, is used to determine where the change in shading panel area ceases to have a considerable influence on the increase of energy saving. The corresponding areas at these points are listed in Table 4. In addition to the fitted curves and scatter plots, Fig. 11 also shows the optimal zone for each angle for horizontal and vertical shading panels. Beyond the optimal zone, i.e. where the total area of shading panels is larger than that at the elbow point, each 1 m^2 increase of panel area results in an improvement of energy saving less than 0.05%. The shading panel configurations of those points falling within the optimal zones can be recommended for energy efficient building designs as they are optimized for energy saving. For example, horizontal shading panels with a separation of 0.23 m (12 panels per wall surface in the simulation) and a length of 0.2 m or vertical shading panels with a separation of 0.46 m (13 panels per wall surface) and a length of 0.6 m can be selected as the optimal configurations at the angle of 30°. The optimal configurations for shading panels of each type and angle are concluded in Table 4. They are also illustrated in the Fig. 13 and Fig. 14 for a clearer visualization. It should be noted that the optimal configurations, and the corresponding areas, are slightly different for different angles. The total areas of optimized horizontal and vertical shading panels at the angle of 60° are 56% and 40% smaller than that at the angle of 90°, respectively. However, the difference in optimal areas is relatively small between the angle of 60° and 30° (21% and 0% for horizontal and vertical shading panels, respectively). Meanwhile, the maximum of energy saving within the optimal zone for shading panels at a small angle (8.6% for both horizontal and vertical panels at an angle of 30°) is greater than that at a large angle (6.8% and 5.2% for horizontal and vertical panels at angle of 90°).

3.4. Practical implications

The optimal configurations with an angle of 30° were then applied to the real case Concord type PRH model (Figs. 1b and 2) to estimate the actual energy saving. After adding the optimal shading panels, a considerable 8.0% in the overall energy saving can be achieved for westward-facing flats, and the energy saving for the master bedroom with larger shaded areas can even be up to 9.7%. Such energy saving potentials are comparable to those obtained from the simplified model and thus confirm the applicability and effectiveness of opaque façade shading in practice. Nevertheless, in reality, the energy saving of adding shading panels with the optimal configurations may vary according to the shaded areas in different rooms.

When discussing the practical application of shading panels on opaque façades, one should also consider issues such as safety, relevant statutory regulations, choice of materials etc. Local climate conditions and natural hazards, e.g. typhoons in Hong Kong, can restrict the design and selection of façade shading. To fulfill safety requirements, safety features may need to be integrated in the façade shading panels, e.g. anti-sway restraints. Furthermore, the wind force on individual shading panels and the connections between façade features and buildings' main structure should be simultaneously evaluated and verified in compliance with other applicable building codes and standards, e.g. *Code of Practice on Wind Effects in Hong Kong* [49] *and Code of Practice for Dead and Imposed Loads* [50].

With reference to the building codes and standards in different countries, apart from safety requirements, the specific shading configurations to be adopted may also need to follow certain restrictions. For instance, the *Practice Note for Authorized Persons APP-156* [44] in Hong Kong controls the maximum length of external shading from the wall (750 mm) in order not to cause obstruction, the Chinese Standard *JGJ 237-2011* [51] states that an increase in the length of panels will improve the shading coefficient until it is larger than the separation between panels, and the *Code on envelope thermal performance for buildings* [52] in Singapore recommends that the length of shading panels should not be 3 times larger than the separation at a tilt angle of 0°, and the angle of tilt should be less than 50°. In practice, the configurations of

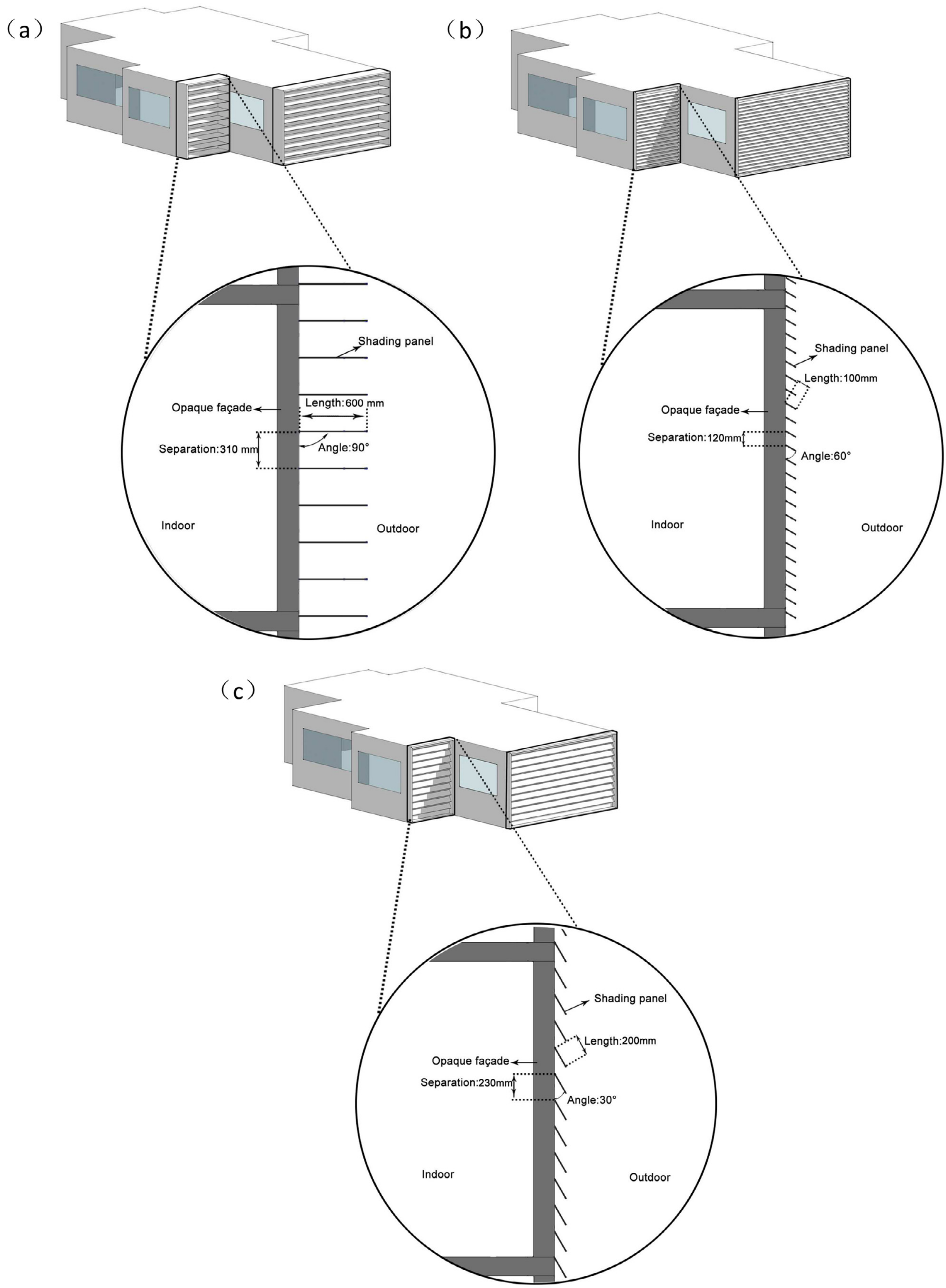

Fig. 13. Sectional views of the optimal configurations for horizontal shading panels at an angle of (a) 90°, (b) 60°, and (c) 30°.

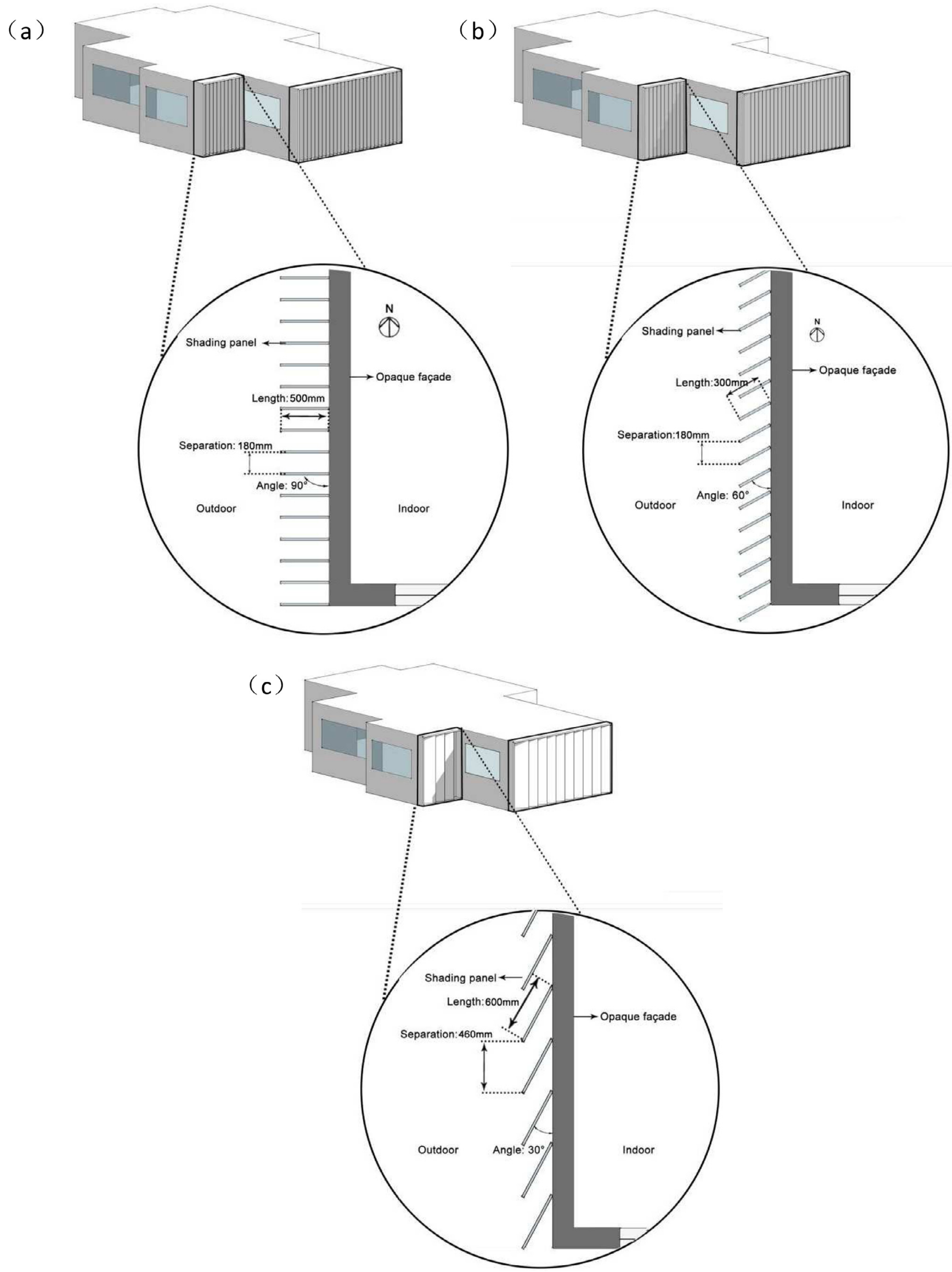

Fig. 14. Floor plan views of the optimal configurations for vertical shading panels at an angle of (a) 90°, (b) 60°, and (c) 30°.

Table 5
Energy saving coefficients for horizontal projection ratio (R_0) and vertical projection ratio (R_1) shading panels at different tilt angles.

R_0	90°	60°	30°	R_1	90°	60°	30°
0.1	0.071	0.080	0.044	0.1	0.016	0.018	0.012
0.2	0.155	0.204	0.176	0.2	0.040	0.063	0.061
0.3	0.232	0.323	0.343	0.3	0.067	0.125	0.151
0.4	0.302	0.423	0.497	0.4	0.095	0.196	0.267
0.5	0.362	0.503	0.617	0.5	0.124	0.268	0.388
0.6	0.414	0.567	0.706	0.6	0.153	0.338	0.500
0.7	0.459	0.617	0.771	0.7	0.181	0.404	0.595
0.8	0.498	0.658	0.817	0.8	0.208	0.463	0.671
0.9	0.532	0.690	0.852	0.9	0.234	0.516	0.733
1.0	0.562	0.717	0.878	1.0	0.259	0.563	0.781
1.1	0.588	0.739	0.898	1.1	0.283	0.605	0.819
1.2	0.612	0.757	0.913	1.2	0.307	0.641	0.849
1.3	0.632	0.773	0.925	1.3	0.328	0.673	0.872
1.4	0.651	0.786	–	1.4	0.349	0.701	0.892
1.5	0.667	0.797	–	1.5	0.369	0.725	0.907
1.6	0.682	0.807	–	1.6	0.388	0.747	0.920
1.7	0.695	–	–	1.7	0.406	0.766	0.930
1.8	0.707	–	–	1.8	0.423	0.783	–
1.9	0.718	–	–	1.9	0.439	0.798	–
2.0	0.729	–	–	2.0	0.455	0.811	–
2.1	–	–	–	2.1	0.469	0.823	–
2.2	–	–	–	2.2	0.483	0.834	–
2.3	–	–	–	2.3	0.496	0.844	–
3.0	–	–	–	3.0	0.573	–	–

Note: "-" indicate that this ratio is no recommended.

shading panels are restricted and varied in different project situations, but the integrated design of the architectural elevation with the façade shading configurations should consider the building energy efficiency. Based on the maximum energy saving (V_{max}) of tilt angle of 30°, the energy saving coefficients with the different projection ratio R_0 (Length/Separation) for horizontal shading and R_1 (Length/Separation) for vertical shading are also provided in detail in Table 5 to guide the design of façade shading features. This parametric study explicitly provides the relationships between the parameters of shading panels and the energy saving effect within the optimal zones for the architects to design buildings with better energy performances.

4. Conclusion

The newly developed SRY weather data was employed in this building energy simulation study to consider the impacts of climate change on summer conditions for the high-density urban environment of Hong Kong. A total of 252 simulations were performed (126 cases each for horizontal and vertical shading panels with different combinations of panel parameters – angle, length, and number/separation) to examine the energy saving potentials of applying shading panels on opaque building façades and to obtain the optimal configurations for shading panel designs. Since this new design feature has not been implemented in real-case projects yet, there are no available field measurements to validate the results. Although the current study focused on shading opaque façades, the findings can be extended for a wider range of application, including curtain walls, windows, or the half wall-half window façades. If these shading panels could be applied on the transparent façade, the energy performance of this strategy would definitely be enhanced due to the greater amount of insolation blocked through the windows. However, the issues of window obstruction and the visual comfort of occupants need to be considered.

From the preliminary tests, opaque façades facing the west and southwest are found to be the most energy sensitive orientations for the application of shading panels. Subsequent parametric analyses conducted for the westward-facing façade show an interesting relationship between energy saving rates and the length and the number of shading panels which reaches a plateau when the parameters are increased to a particular value. This value is smaller for shading panels at a lower angle. Results also suggest that the increase in energy saving by changing the angle for vertical shading panels is more obvious and effective than for horizontal shading panels, but the latter can achieve the maximum energy saving with a smaller total area of shading panels. Optimal configurations for shading panels are identified from the zone where the energy saving effect has the most sensitive response to the total area of shading panels. These optimal shading configurations can then be integrated with the design of other façade features (e.g. for aesthetic expressions) at the early design stage or applied to existing buildings with poor energy performance. Taking this study as a starting point, further studies should discuss the practical applications, including but not restricted to cost-benefit analyses, the feasibility of implementation, and the effects on wind flow around façades etc., of this innovative opaque façade shading strategy for high-rise buildings under worsening climate conditions.

The potential energy saving of applying the optimal shading panels can be up to about 8.0% for those rooms with westward-facing façades in Concord type PRH buildings. Therefore, this strategy could make a great contribution to the overall energy efficiency in similar existing high-rise buildings across Hong Kong. Furthermore, the energy saving coefficients within the optimal zones could be systematically documented in a database to help practitioners in selecting the optimal design of façade shading devices to improve the energy efficiency of the newly built estates. Finally, the workflow described in this study could be adopted to conduct further investigations on the optimization of façade designs facing different orientations.

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Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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