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Research paper

Designing energy-efficient and visually-thermally comfortable shading systems for office buildings in a cooling-dominant climate

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ABSTRACT

Windows and their control elements, including shading systems, are among the most critical building components affecting both energy consumption and occupant comfort. With the increasing demand for full-glazed facades, designers and researchers are actively devising advanced control strategies to address the challenges posed by excessive sunlight penetration and heat transfer. These strategies aim to harmonize the benefits of natural light with the need for comfortable indoor environments and energy consumption reduction. This study investigates the impact of external shading configurations for an office room in Tehran, categorized as group B in the Köppen climate classification, to reduce total building energy consumption and improve occupant thermal and visual comforts. The shading parameters include shading angle, shading depth, and the number of shading slats. More specifically, this study analyzes and compares two design configurations for the considered office room. The first configuration consists of a single southern window with horizontal shading, whereas the second configuration consists of two windows on the south and west, one being horizontal shading on the southern side and the other being vertical shading on the western side. There are a total of 1330 models investigated from which 20 models are selected as the most suitable solutions. Finally, this paper examines the effect of each design parameter on the overall performance of each configuration in terms of energy efficiency and visual-thermal comfort.

1. Introduction

Given the increasing environmental and economic concerns regarding energy consumption in urban environments, improving the energy efficiency of commercial and residential buildings has been an important research area over the past few decades. From a different standpoint, occupant comfort within a building affects the quality of life, health, and productivity of indoor people (Roman et al., 2020). However, reducing building energy consumption and improving occupant comfort simultaneously is a significant challenge (Godithi et al., 2019; Santos, 2020). Notably, as the building envelope is a boundary between the inside and outside of a building, its design is critical to achieving a reliable trade-off between energy consumption and indoor occupant comfort.

With the appropriate design of building envelope components such as the window-to-wall ratio (WWR) (Acar et al., 2021; Nazari et al., 2022), orientation (Nazari et al., 2022), use of natural ventilation (Hu et al., 2023), insulation, and windows and shading devices, the desired "nearly zero-energy buildings (nZEB)" could be achieved (Saini et al., 2021; Xu et al., 2016). Among these components, windows, as one of the

Abbreviations: WWR, Window-to-wall ratio; SHGC, Solar heat gain coefficient; nZEB, Nearly zero-energy buildings; sDA, Spatial daylight autonomy; UDI, Useful daylight illuminance; ASE, Annual sunlight exposure; MDF, Modular dynamic façade; IDA, Image density atlas; UEBs, Ultralow-energy buildings; PPD, Predicted percentage of dissatisfaction; EUI, Energy use intensity; FSR, Façade shading ratio.

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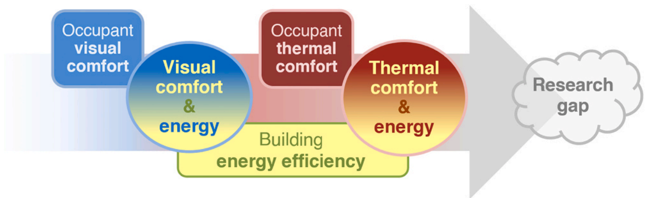

Fig. 1. An overview of the background study.

critical connections between architecture and building energy performance (Yong et al., 2017a), are about five times more important than the other components (Yong et al., 2017b). Besides, the daylighting and sunlight penetration through windows directly affect occupants' visual and thermal comforts (Chi et al., 2020; Huang et al., 2014; Kaasalainen et al., 2020). Windows are also crucial from the architectural point of view concerning occupants' satisfaction and perception of the space affected by building appearance, outside view, and natural ventilation (Moscoso et al., 2020). However, in the absence of control components such as shadings, windows can cause overheating (Moscoso et al., 2020), glare (Matin and Eydgahi, 2021), and an increase in cooling energy consumption, despite reducing heating and artificial lighting energy (Moscoso et al., 2020). Implementing solar control systems using shading devices is a practically straightforward method for regulating the entry of sunlight into a building's interior (Song et al., 2021). An appropriate shading design prevents overheating by blocking unwanted solar radiation in the summer and allowing it to penetrate in the winter, which result in the reduction of heating and cooling energy consumptions (Ishac and Nadim, 2021; Zhao and Du, 2020). Moreover, a suitable shading design should consider occupants' thermal and visual comfort. Furthermore, appropriate shading systems can be integrated into older buildings during renovation, while also upgrading energy-consuming devices like heating, ventilation, and air conditioning (HVAC) systems (Liu et al., 2023a). This integration can include the application of modern technologies such as smart sensors, big data analyses, and machine learning algorithms (Liu et al., 2023b).

Section 1.1 provides a literature review on building energy efficiency and occupant well-being, focusing particularly on visual and thermal comfort metrics (Fig. 1). The review begins by exploring how window and shading configurations affect energy efficiency. Subsequently, it investigates the connection between occupant visual comfort and energy consumption. Finally, the literature investigates the interplay between occupant thermal comfort and building energy usage. Within this review, a research gap is identified, and the study's distinct contributions are highlighted.

1.1. Background study

Many studies have examined the effect of windows and shading devices on building energy consumption in different climates. Al-Saadi and Al-Jabri (2020) achieved a residential building energy consumption between 16.56% and 25.86% in different cities in Oman by optimising the building envelope. Krarti (2022) studied a rotating overhang system for office buildings in the warm climates of the United States and obtained a potential energy saving of around 40%. Nazari et al. (2022) investigated various architectural parameters including the WWR, building orientation, and the aspect ratio of an elliptical commercial building; they found a WWR of 80% with a no-rotation orientation to be an appropriate choice for reducing building energy consumption and improving occupant comfort. Ahmad et al. (2021) investigated the effect of shading devices combined with varying HVAC set points to diminish building energy usage in a south-facing historic building in Egypt. They identified a potential energy saving of 46% by implementing a horizontal exterior shading at a specific HVAC temperature set point. In warm climates, a well-planned shading design and carefully chosen window configurations play significant roles in decreasing the amount of building energy use. This reduction in energy consumption applies to various types of buildings, making it a crucial consideration in sustainable architectural practices.

Golzan et al. (2021) achieved a more than 40% reduction in building energy consumption by optimising a modular dynamic façade (MDF) in a hot climate in Iran and found an angle of 30° as the optimum angle. Nazari et al. (2023a) explored shading options for an office building in Tehran. Their results showed that east- and west-facing windows reduced lighting energy but doubled total energy consumption compared to south-facing windows. They also concluded that shading angle and slat number had a more significant effect than shading depth on energy usage. In another study, they compared shading designs in Tehran's dry climate and Auckland's warm, temperate climate. They found that the office building in Tehran required more cooling and heating energy compared to the one in Auckland, while they had comparable lighting energy consumptions (Nazari et al., 2023b). Rana et al. (2021) optimised a shading device in Bangladesh and indicated that the optimal height of the shading was equal to half of the window height, leading to an around 7% reduction in building energy consumption.

In recent years, the application of optimisation methods has attracted significant attention as an effective approach to enhancing shading configurations with the goal of reducing building energy consumption. This strategy has proven to yield favourable outcomes, contributing to improved energy efficiency in various architectural contexts. Consequently, a growing number of researchers have embraced these optimisation techniques as a valuable tool in their investigations. Vukadinoviććc et al. (2021) conducted an optimisation study in Serbia which showed that suitable shading specifications depended on the facade orientation; that is, narrow shadings were more efficient on southern facades, whereas for eastern and western facades, shadings wider than one meter were more effective. Dutta et al. (2017) studied the application of movable exterior shading systems that showed a 9.8% reduction in annual energy consumption, with a highest reduction of 14.9% in June. Ghosh and Neogi (2018) proposed a new shading design that reduced the total building energy consumption by up to 4.6% by blocking sunlight radiation in summer and allowing sunlight penetration the in winter.

The implementation of shading devices in China has proven to be effective in the reduction of building energy consumption and has gained significant attention within the context of sustainable architecture and urban development. Huo et al. (2020). showed that by using external shadings in cold regions of China, as a common method for reducing energy consumption (Huo et al. 2017), it was possible to increase the total energy saving by up to 21.8% in ultralow-energy buildings (UEBs). Another study in China demonstrated that the total energy saving increased by increasing the shading angle from 0° to 180° (Huo et al., 2021). A study by Lai et al. (2017) on the solar heat gain coefficient (SHGC) in selected cities showed that an optimal SHGC could save 37.8% and 24.8% of the total building load in the USA and China, respectively.

An appropriate shading design also contributes to improving occupants' visual comfort by controlling natural light and preventing glare. Acosta et al. (2016) studied the impact of window shape and location on daylight distribution; they observed better performance of higher-up windows to light the back of the room, whereas no significant effect was reported for the window shape. Previous studies showed that horizontal shadings generally lead to better results in comparison with vertical ones (Matin and Eydgahi, 2021). Several researchers optimised shadings to use daylight appropriately, although different results were reported depending on the implemented method. Khidmat et al. (2022) achieved a complete removal of ASE and a UDI enhancement of about 50% by optimising an expanded-metal shading in Japan (Valitabar et al., 2022) optimised a multi-layer blind system by which they achieved a 44% improvement in daylight for an office room in Tehran, Iran. Using an internal adaptive shading by Mangkuto et al. (2022) for a high-rise office building in a tropical climate resulted in more than 74% spatial daylight autonomy (sDA300/50%) and less than 12% annual sunlight exposure (ASE1000,250). An evaluation of light shelves in Toronto, Canada, showed the potential of increasing useful daylight illuminance (UDI), especially within the first 6 m near windows (Berardi and Anaraki, 2015). The results reported by Kaasalainen et al. (2020) revealed the necessity of shadings for daylight penetration control in the Scandinavian countries, where the shading is vital due to low sun altitude angles (Obradovic and Matusiak, 2019). A sensitivity analysis showed that WWR, glazing, blind type, and slat angle were the most influential parameters on energy use intensity (EUI) and daylight (Singh et al., 2016). De Luca et al. (2022) studied the multi-objective optimisation of shadings for a classroom in Tallinn, Estonia. They demonstrated the possibility of an around 90% improvement in the UDI, as well as a 30% reduction in the EUI. Both external and internal shading solutions have demonstrated their effectiveness in enhancing occupant visual comfort and optimising daylighting conditions within buildings.

A new method of examining the effect of louver design on the amount of daylight has increased the adapted UDI by 9.8%, 13.1%, and 22.7% in static, seasonally adjusted, and dynamic external shadings, respectively (Huo et al., 2020). As mentioned previously, increasing the UDI may cause glare near windows. A survey of high-rise buildings in Malaysia showed the need for curtains to prevent glare in some hours (JieKwong, 2020). Xie and Sawyer (2021) recently applied machine learning algorithms to study the performance of automated shading systems in reducing glare while increasing daylight. Optimising the façade shading ratio (FSR) through the use of an image density atlas (IDA) resulted in reducing 38.5% of glare and 54% of solar radiation in a gymnasium with an acceptable range of illuminance loss (Fan et al., 2022). In 2020, Noshin et al. (2020) showed that an optimised shading in Pakistan could increase the UDI around 10.6% and 11.5% in winter and summer, respectively. In another research work, shading optimisation in Malaysia increased the UDI between 4.7% and 17.5% at different times of the year (Bahdad et al., 2020). Ishac and Nadim (2021) evaluated a school with a glass facade in Cairo using a systematic method to optimise the shadings the results of which showed a 1% enhancement in the UDI. Besides, Sedaghatnia et al. (2021) showed the possibility of increasing the UDI by up to 70% simultaneous with a 59% reduction in building energy consumption in Iran by optimising window orientation, WWR, and shadings specifications. More recently, the acceptable performance of internal shadings for providing adequate annual daylight was demonstrated by simultaneously considering adaptive and fixed shadings in the tropical climate (Mangkuto et al., 2022). It is important to note that a poorly designed shading system can sometimes lead to glare issues rather than enhancing visual comfort. Therefore, it is advisable to conduct an analysis that also considers the probability of glare.

Importantly, the relation between energy consumption and daylighting is generally nonlinear; i.e., improving one may worsen the other. Therefore, multi-objective optimisation methods have been widely used by researchers to overcome this challenge (Pilechiha et al., 2020). Lim et al. (2020) examined various shading types; among them, the egg crate was considered the best for reducing cooling energy consumption and increasing the UDI. A multi-objective optimization approach facilitated achieving a trade-off between energy efficiency and user comfort by modifying the building envelope parameters including WWR, wall material, glass type, and shading devices (Lakhdari et al., 2021). It is important to note that while efforts to enhance visual comfort within a building are commendable, they can sometimes inadvertently result in an increased cooling load. This occurs because measures to optimise natural light often involve larger windows or increased daylight penetration, which can also introduce more solar heat into the interior space. Thus, it is essential to study both aspects concurrently to mitigate any adverse effects.

Another critical factor in reducing energy consumption is thermal comfort, which substantially affects occupants' health and productivity

Table 1
A summary of some previous studies.

Variables	Objectives	Results	Ref.
• Window system • Window location • Window dimensions	• Building energy load (EUI) • Daylight (sDA, ASE) • View to the outside (QV)	• 12% improvement in the EUI • Satisfactory QV • Daylight improvement	(Pilechiha et al., 2020).
• External light shelves • Internal light shelves	• Daylight improvement	• External light shelves are more efficient in controlling daylight • The angle of 20° is most appropriate • Around 10–12% improvement in daylight	(Noshin et al., 2020).
• Responsive horizontal and vertical louvres	• Indoor illuminance improvement	• Better visual performance of horizontal louvres • Better performance of louvres on the western and eastern façades in comparison with the southern and northern façades • Better performance in hot seasons	(Matin and Eydgahi, 2021)
• Building envelope • Building energy supply • Fenestration • Shading material • Control methods	• Visual comfort • Thermal comfort	• 77% reduction in building energy consumption • Improvements in visual and thermal comforts	(Rabani et al., 2021).
• Light shelves dimensions • WWR	• UDI	• UDI improvement for the first six meters near the window • Better daylight distribution • Glare issue for WWRs of more than 35%	(Berardi and Anaraki, 2015)
• External Venetian blind • Climate condition • Building orientation • WWR • Control purpose	• Activation threshold • Slat angle • DGI • Lighting energy demand	• Larger slat angle when focusing on comfort • Greater threshold irradiance when focusing on energy load	(Yun et al., 2017).
• Window system • Louvres reflectivity	• Thermal performance • Daylight	• Best performance for Low-E glazing • Better thermal and daylighting performance with more blind reflectivity	(Huang et al., 2014).
• Internal shading optimization • Fixed and adaptive shadings • Number and width of slats	• Annual daylight performance	• $sDA_{300/50\%}$ and $ASE_{1000,250}$ are only influenced by the orientation	(Mangkuto et al., 2022).
• Shading angle • Shading depth • Number of slats • Two configurations: 1. Southern window 2. Southern and western windows	• EUI • UDI • PPD • Daylight distribution • Thermal comfort map	• Better performance for two shadings • Better outcomes with upward and downward shading angles of up to 20° for Configuration 1 and acute angles for Configuration 2	This study

(continued on next page)

Table 1 (*continued*)

Variables	Objectives	Results	Ref.
		• 12.1% improvement in UDI for Configuration 1% and 59.60% for Configuration 2 • 7.9–29% reduction in EUI for Configuration 1% and 31.29% for Configuration 2	

(Li et al., 2021). Several studies have been conducted on designing shadings to reduce energy consumption and predicted percentage of dissatisfaction (PPD). Dagher et al. (2022) studied the influence of shading devices on occupant thermal comfort in a Minneapolis school building. Their findings suggested that a well-designed shading system could potentially reduce cooling hours by 4%, thereby enhancing thermal comfort for occupants. Xu et al. (2022a) found the possibility of an 18.5% reduction in overheating, affecting occupant thermal comfort and energy consumption, by using a horizontal shading in a high-rise residential building in some severely cold regions of China. Yun et al. (2017) showed that implementing control methods with Venetian blinds could increase occupant comfort while decreasing cooling and lighting energy consumptions. It should be noted that different configurations of this type of shading would affect occupant comfort differently, and it would be most beneficial if they are automated (Carletti et al., 2016). Effective shading design can significantly improve thermal comfort within a building while concurrently reducing its overall energy consumption. This dual benefit underscores the importance of shading strategies in architectural and environmental design.

Ebrahimi-Moghadam et al. (2020) used optimized shading specifications to reduce energy consumption and increase thermal comfort in a residential building. They reported the optimal angle, depth, and number of shadings for southern, western, and eastern facades. In another research work, Zhao and Du (2020) achieved 8% and 26% reductions in the PPD and energy consumption, respectively, by examining the physical characteristics of windows and glasses in an office. A recent study retrofitted a building to achieve zero-energy performance in Norway. Besides, two specifications of shadings, including angle and position, were evaluated to reduce energy consumption while increasing indoor comfort (Rabani et al., 2021). However, cold regions usually experience overheating in summer which can be alleviated by using appropriate shading devices (Xu et al., 2022b). A well-executed shading design offers advantages in both hot and cold climates. This adaptable strategy underscores the versatility of shading solutions across diverse climatic conditions.

Windows are critical components of the building envelope that directly affect its energy consumption, as well as the thermal and visual comforts of its occupants, by facilitating heat transfer, natural ventilation, and daylight penetration. However, using control devices such as shadings is often required and should be based on appropriate data and analyses to simultaneously achieve these three objectives. As mentioned earlier, although many previous studies examined and optimised shading specifications considering one or two of these objectives, only a few investigations considered all three objectives. Importantly, the three-objective evaluation of a shading system is particularly challenging mainly due to the conflicting requirements of the three objectives.

Table 1 summarizes the variables, objectives, and results of some previous studies in this area. It should be noted that these studies did not provide a detailed investigation of the $UDI_{100-2000}$ and $UDI_{\geq 2000}$ distributions as well as the occupant thermal comfort map (including the required cooling and heating). This study aims to fill this research gap by providing such maps that can visually guide architects and decision-makers to better understand occupant comfort in buildings, which could result in better building designs.

In this study, two design configurations of a typical office room in Tehran, Iran, are considered to parametrically investigate the impact of the arrangement of windows and shading slats using a data-driven approach. Configuration 1 consists of a single southern window with a horizontal multi-slat shading, while Configuration 2 consists of two windows on the southern and western sides of the room with horizontal and vertical shadings, respectively. The design parameters include the shading angle, depth, and number of slats with the objectives of reducing EUI and PPD while increasing UDI. A total number of 1330 models are analysed and 20 models are selected as the most suitable trade-offs among building energy efficiency, occupant thermal comfort, and occupant visual comfort. Moreover, two other visual comfort indices concerning glare are evaluated for the selected models. Finally, the maps of daylight distribution and thermal comfort condition are presented for these solutions.

2. Problem, materials, and methods

In this section, the statement of the design problem, modelling procedure, and performance evaluation method used in this study are explained.

2.1. Problem statement and modelling approach

In this study, a 4 m × 8.5 m × 3.1 m office room on the middle floor of a building in Tehran, Iran, is evaluated (Fig. 2a). Two design configurations are considered: Configuration 1 consists of one 1.5 m × 3.6 m southern window in the centre of the wall (Fig. 2c), whereas Configuration 2 consists of two similar windows on the south and west orientations (Fig. 2d). Table 2 and Table 3 summarize the thermal specifications of the building and windows, respectively, which are typical for office buildings in Iran (Ebrahimi-Moghadam et al., 2020). As can be seen from Fig. 2b, the multi-slat shading model consists of three variables: number of slats n, depth d, and slat angle α. In this study, $1 \leq n \leq 5$, 0.1 m $\leq d \leq 0.7$ m, and α varies between zero (completely 'downward' for horizontal and 'clockwise' for vertical shadings) and 180° (completely 'upward' for horizontal and 'counter-clockwise' for vertical shadings).

The objectives of this study are to reduce building energy consumption and improve occupant thermal and visual comforts for the abovementioned model. Therefore, EUI, PPD, and $UDI_{100-2000}$ are chosen as the indices for the abovementioned objectives, respectively. The EPW file of Tehran (Group B (arid) in the Köppen climate classification) considered in this study belongs to Mehrabad International Airport with the latitude and longitude of 35.683° N and 51.317° E, respectively, located in an elevation of 1190 m (Climate.onebuilding.org, 2021).

The office room is modelled in Rhinoceros Grasshopper. To analyse the energy performance and occupant thermal and visual comforts, the *Ladybug Tools* (2021) is adopted and a parametric study is performed using the plugin *Colibri* of the *TT Toolbox* 1.9 (2020). Finally, the platform *Design Explorer* is used to select the most desired solutions among all 1330 models by a trade-off among EUI, PPD, and UDI (see Fig. 2e).

2.2. Evaluation method

UDI is a widely-accepted metric for daylight evaluations and indoor illuminance measurements. It contains two lower and upper thresholds, defining three metrics $UDI_{overlit}$, UDI_{useful}, and $UDI_{underlit}$ (Chauvel et al., 1982), as follows

$$UDI = \frac{\sum_i (wf_i . t_i)}{\sum_i (t_i)} \in [0, 1] \quad (1)$$

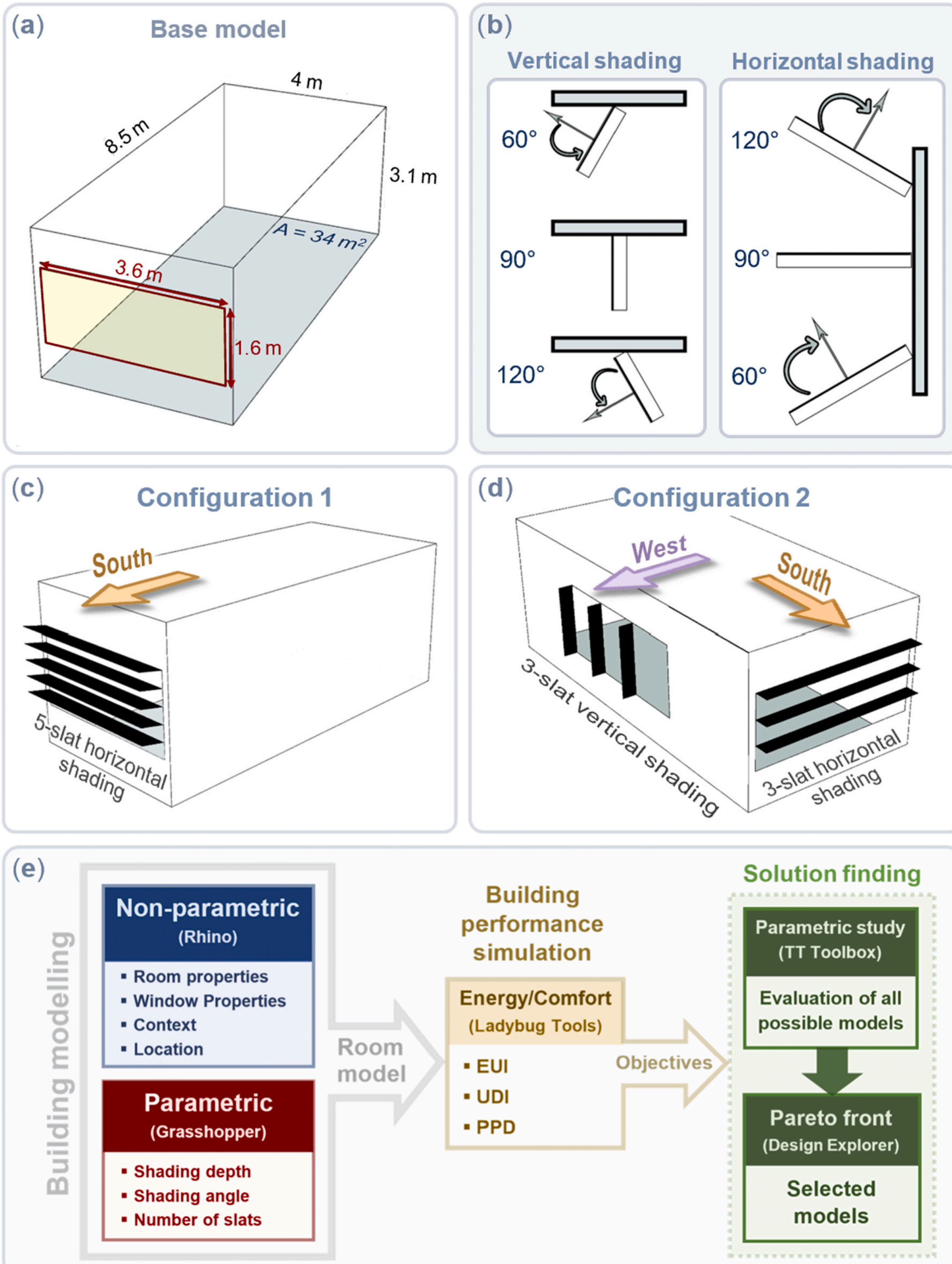

Fig. 2. (**a**) Geometry and dimensions of the base model. (**b**) Vertical and horizontal shading slats in different angles. (**c**) Design specifications of Configuration 1. (**d**) Design specifications of Configuration 2. (**e**) Flowchart of the solution-finding process for the design problem.

$$\mathrm{UDI_{overall}} \quad \text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{\mathrm{Daylight}} > E_{\mathrm{Upper}\ limit} \\ 0 & \text{if} \quad E_{\mathrm{Daylight}} < E_{\mathrm{Upper}\ limit} \end{cases} \tag{2}$$

$$\mathrm{UDI_{useful}} \quad \text{with} \quad wf_i = \begin{cases} 1 \quad \text{if} \quad E_{\mathrm{Lower}\ limit} < E_{\mathrm{Daylight}} \le E_{\mathrm{Upper}\ limit} \\ 0 \ \text{if} \ E_{\mathrm{Daylight}} \le E_{\mathrm{Lower}\ limit} \ \text{or} \ E_{\mathrm{Daylight}} > E_{\mathrm{Upper}\ limit} \end{cases} \tag{3}$$

where E, wf, and t denote indoor illuminance, weighting factor, and time, respectively. In this study, $\mathrm{UDI}_{100\text{–}2000}$ is chosen as the desired occupant visual comfort index while $\mathrm{UDI}_{2000\text{–}3000}$ is also evaluated for the selected models.

To evaluate occupant thermal comfort, the index PPD is chosen. It is a function of Predicted Mean Vote (PMV) which can be calculated using the correlation developed by Fanger (Shaw, 1972) expressed as

Table 2
Thermal specifications of the base model envelope.

Surface	Material	Roughness	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)	Thermal absorptivity (-)	Solar absorptivity (-)	Overall U-Value (W/m^{2}K)
Interior wall	Gypsum board	Medium smooth	0.02	0.16	800	1090	0.9	0.4	2.581
	Air gap	-	0.15	-	-	-	-	-	
	Gypsum board	Medium smooth	0.02	0.16	800	1090	0.9	0.4	
Exterior wall	Brick	Medium rough	0.10	0.89	1920	790	0.9	0.7	0.459
	Heavyweight concrete	Medium rough	0.20	1.95	2240	900	0.9	0.7	
	Insulation board	Medium rough	0.05	0.03	43	1210	0.9	0.7	
	Air gap	-	0.15	-	-	-	-	-	
	Gypsum board	Medium smooth	0.02	0.16	800	1090	0.9	0.4	
Interior ceiling	Lightweight concrete	Medium rough	0.10	0.53	1280	840	0.9	0.5	1.449
	Air gap	-	0.18	-	-	-	-	-	
	Acoustic tile	Medium smooth	0.02	0.06	368	0.9	0.9	0.3	
Roof	Metal roofing	Medium smooth	0.002	45.0	7680	418	0.9	0.6	0.345
	Insulation board	Medium rough	0.24	0.05	265	837	0.9	0.7	
	Metal decking	Medium smooth	0.002	45.0	7680	418	0.9	0.6	

Table 3
Thermal specifications of window layers.

Specification	Exterior layer	Gap	Interior layer
Material	Glazing	Air	Glazing
Thickness (m)	0.003	-	0.003
Conductivity (W/mK)	0.900	-	0.900
Solar transmittance (-)	0.837	-	0.837
Visible transmittance (-)	0.898	-	0.898
Infrared transmittance (-)	0	-	0
Front side infrared emissivity (-)	0.840	-	0.840
Back side infrared emissivity (-)	0.840	-	0.840
Overall U-value (W/m^{2}K)	900	2.407	900

$$\mathrm{PPD} = 100 - 95\exp(-0.03353 \times \mathrm{PMV}^4 - 0.2179 \times \mathrm{PMV}^2) \tag{4}$$

Index PMV depends on several parameters including the mean radiant temperature t_{Ra} (°C), air temperature t_A (°C), relative air velocity V (m/s), relative humidity φ (%), water vapor pressure P_A (Pa), and two personal variables (thermal insulation of the clothing I_{Cl} (m^{2}K/W) and metabolic rate M' (met)). Moreover, the index EUI is used to evaluate the building energy consumption considering cooling, heating, and lighting, as follows

$$TE = LE + HE + CE \tag{5}$$

where *TE*, *EE*, *HE,* and *CE* denote *total*, *lighting*, *heating*, and *cooling energies*, respectively.

In the final step, two established indices for daylight glare probability (DGP) (Wienold, 2009) and daylight glare index (DGI) (Chauvel et al., 1982) are also evaluated for selected models.

The expression for DGP is as follows

$$\mathrm{DGP} = c_1.E_v + c_2.\log(1 + \sum_i \frac{L_{s,i}^2.\omega_{s,i}}{E_v^{c_4}.P_i^2}) + c_3 \tag{6}$$

where E_v [lx] is the vertical eye illumination; $L_{s,i}$ [cd/m^2] is the luminance of the glare source; ω [sr] is the solid angle of the glare source; and P_i is the position index relative to the glare source.

The expression for DGI is given by

$$\mathrm{DGI} = 10\log\sum_{i=1}^{n} G_i \tag{7}$$

where

$$G_i = 0.48\left(\frac{L_s^{1.6}\Omega_i^{0.8}}{L_b + 0.07\omega^{0.5}L_w}\right) \tag{8}$$

where L_s [cd/m^2] is the luminance of the glare source; L_b [cd/m^2] is the average luminance of the interior surfaces of the room which contributes to the visual field of occupant; L_w [cd/m^2] is the average luminance of the window weighted according to the relative areas of sky obstructions and ground; ω [sr] is the solid angle of the window; and Ω [sr] is the corrected solid angle subtended by the window, with weighting factors for different areas depending on their direction with respect to the occupant's line of sight.

3. Results and discussion

Preliminary energy and comfort analyses for the two configurations provided numerical results as follows. For Configuration 1, EUI = 78.05 kWh/m^2, PPD = 9.15%, and UDI = 70.40%, whereas for Configuration 2, EUI = 123.72 kWh/m^2, PPD = 51.22%, and UDI = 12.86%. For the south-faced room, UDI results are more scattered than the others, showing that it is highly affected by the shading design parameters. The following sections discuss the effect of design parameters on the introduced indices.

3.1. Configuration 1: Office room with one window

3.1.1. Shading slat angle

For Configuration 1, the effects of shading angle on EUI, UDI, and PPD are diagrammed in Fig. 3. As can be seen from this figure, the received daylight would generally be reduced by adding a shading slat, except for up to 20°-upward and -downward rotations. The results showed that, compared to the base model, the 10°-upward rotation (100°) of horizontal shading angles resulted in up to 9.8% improvement in the UDI. It was followed by only 3% enhancement with an additional

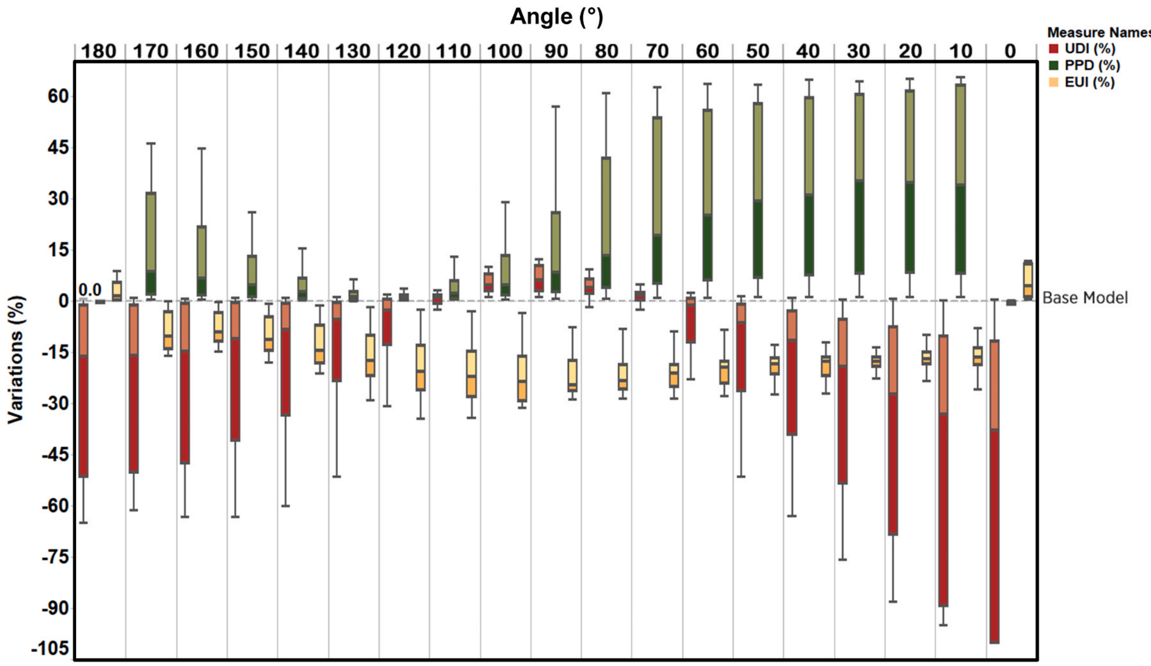

Fig. 3. The effect of shading angle on EUI, UDI, and PPD in Configuration 1.

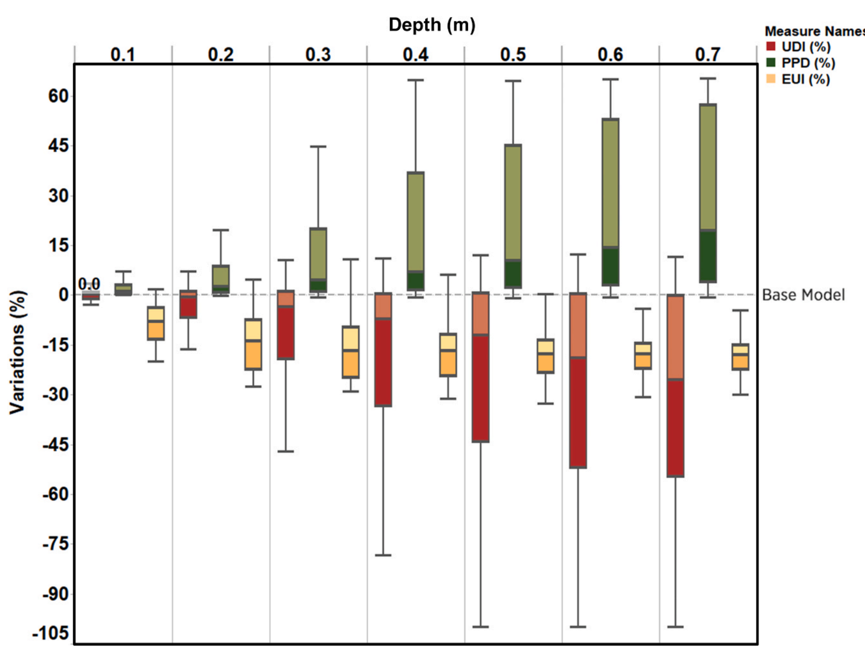

Fig. 4. The effect of the shading depth on EUI, UDI, and PPD in Configuration 1.

10° rotation (110°) while it would be 12.1% for the completely horizontal shading. The downward rotation had a similar impact with 9% and 4.6% increases in the UDI, respectively. These configurations also positively affected EUI and led to a 34.5% reduction at an angle of 110° while a minimum 3.3% improvement in the building energy consumption was achieved. However, the completely vertical shading resulted in the minimum and maximum EUI reductions of 29% and 7.9%, respectively, with an almost similar median to the angle of 110° by 24.7%.

On the other hand, downward rotations up to the angle of 90° negatively affected the occupant thermal comfort and raised it from the maximum by 56.7% with a completely horizontal shading to 65.2% at the angle of 10° (80° downward) and then dropped to similar amount with the base model. Although upward rotation worsened the occupant thermal comfort as well, it is less intense to the point that 30° upward rotation of slats decreased the maximum PPD by 53.3% compared to the completely horizontal shading, reaching 3.4%. It then increased to a maximum of 46% at the angle of 170°, and subsequently fell to an amount close to that of the base model with a completely downward shading.

Both upward and downward shading rotations of more than 20° reduced UDI with an average of 15% and more than twice reduction, respectively, to the point that no parts of the studied office room received the desired $UDI_{100–2000}$ with a complete upward rotated shading. This reduction is less intense with upward rotation and the maximum of UDI fell to 65.1% less at the angle of 180° compared to the base model. On the contrary, downward rotation positively affects the

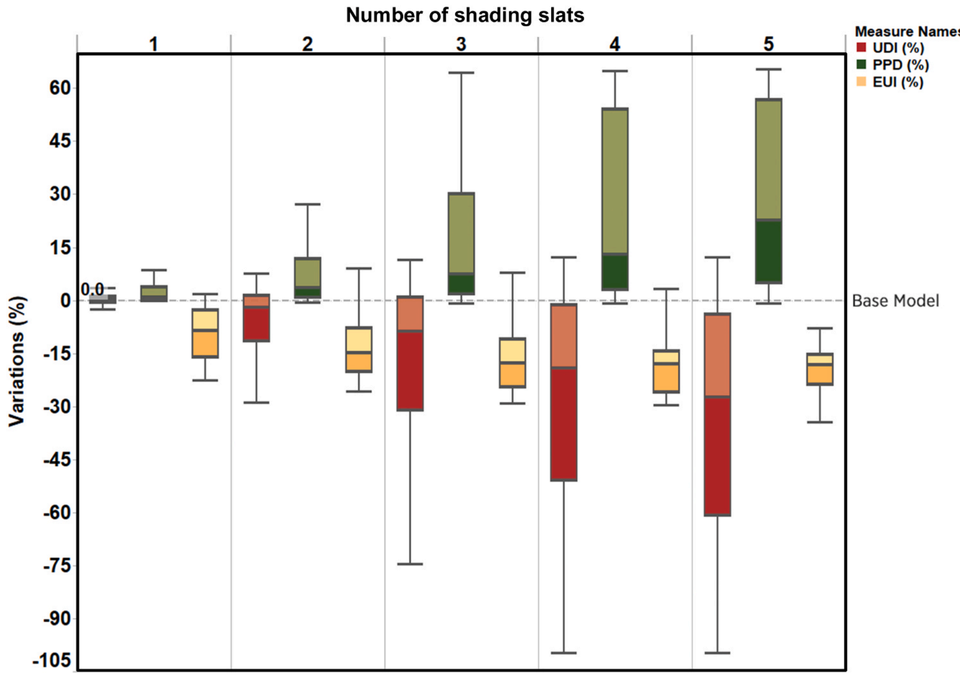

Fig. 5. The effect of the number of shading slats on EUI, UDI, and PPD in Configuration 1.

EUI and the lowest maximum by 13.8% reduction at the angle of 60°. This objective saw an increment by up to 11.4% and 8.6% only with a complete downward and upward rotated shading, respectively.

3.1.2. Shading depth

As shown in Fig. 4, changing the shading depth results in the occupant comfort exacerbation in contrast to the energy efficiency improvement. However, the smallest shading slat resulted in up to 3.1% and 6.8% reduction in occupant visual and thermal comforts, respectively, while the EUI saw a maximum improvement of 20.2%. The worsening trend of the UDI continued to the deepest shading slat, reaching the complete blockage of the daylight and no parts of the room received more than 100 lux. Nevertheless, 75% of the results with all of the shading depth resulted in less than 54.7% reduction of the UDI compared to the base mode. Interestingly, the desired daylight can also be improved in any depth by up to 12.1% with a 0.6 m shading depth, depending on the other two variables of the study. While the minimum of the other index of the occupant comfort (thermal comfort) is almost similar to the base model, the maximum experienced a reduction trend, reaching a 65.2% increment with the widest shading in the PPD; the median of results with 0.7 m of depth, however, was 19.4%. The highest difference between the second quartile (75% of the results) and the maximum occurred with a 0.4-m deep shading.

Despite the occupant comfort, the EUI decreased by widening the

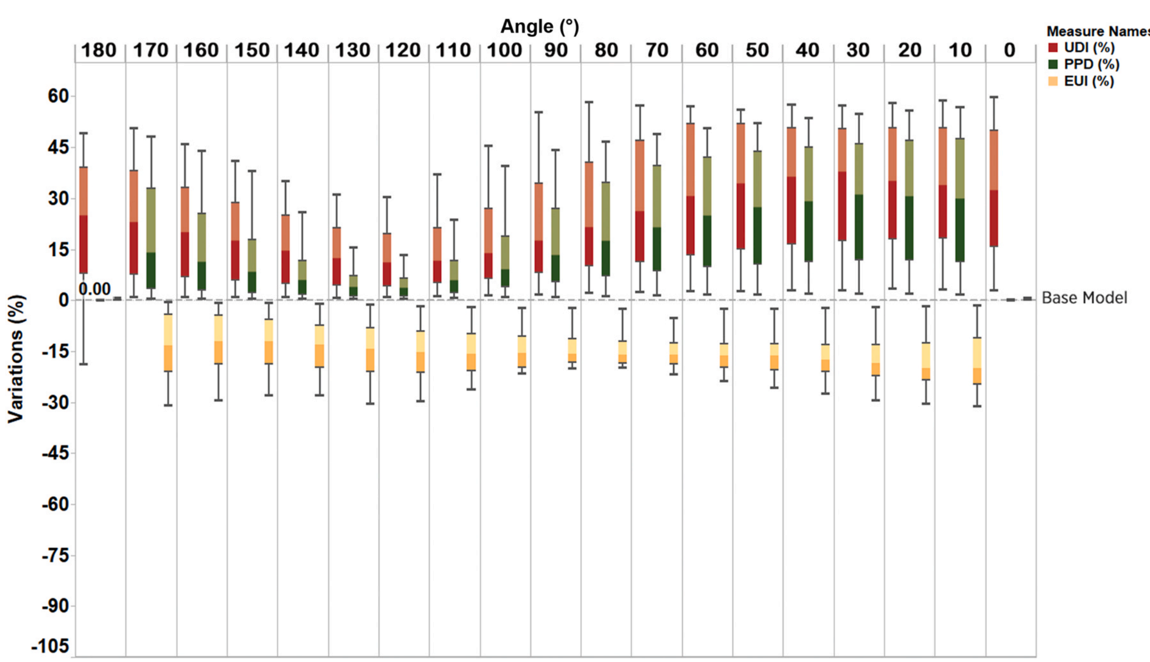

Fig. 6. The effect of the shading angle on EUI, UDI, and PPD in Configuration 2.

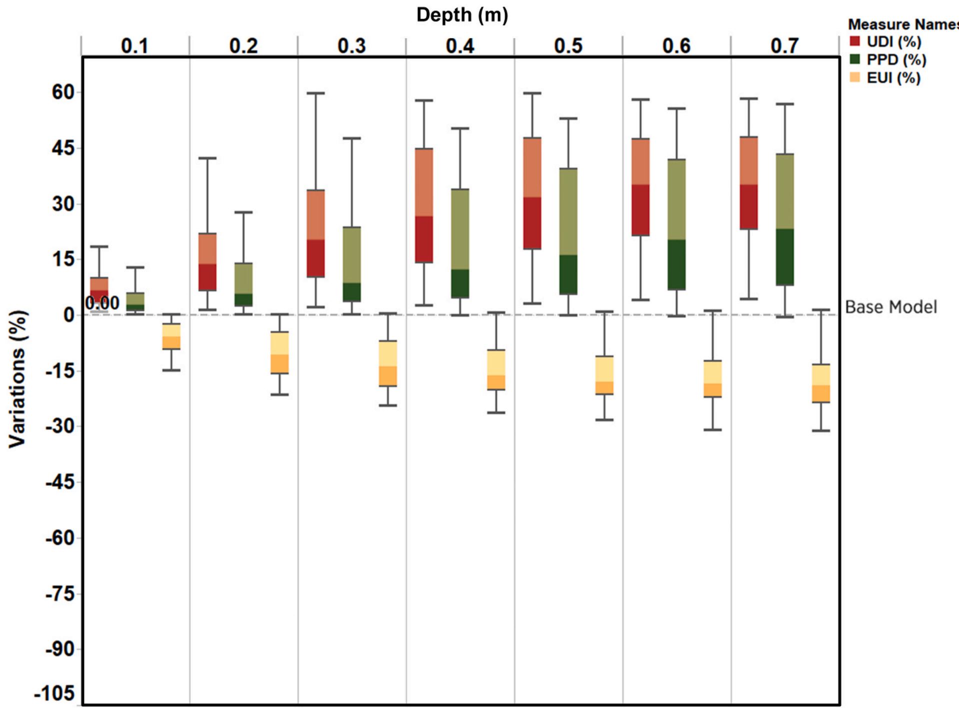

Fig. 7. The effect of the shading depth on EUI, UDI, and PPD in Configuration 2.

shading slat. While the average improvement of the EUI equals 15.5%, the highest reduction in the EUI is achieved by 32.9% with 0.5 m depth of shading, followed by 31.4% with 0.4 m one. However, from 0.1 m depth of shading to 0.4 m, the EUI may increase up to 10.7% depending on the other variables in contrast to the minimum improvement of 4.2% with a deep shading of 0.6 and 0.7 m.

3.1.3. *Number of shading slats*

The effect of the number of shading slats is shown in Fig. 5. Based on the 25% of the results, adding to the number of slats may increase the UDI in all cases and up to 12.1% with 4-slat shading; however, it is more possibly to decreased by an average of 20%. Increasing the number of slats from one to two significantly decreased the minimum UDI from 2.7% reduction compared to the base model to 29.2%, followed by 74.7% with a 3-slat shading while 75% of outcomes are less intense and reduced the UDI by 31.1%. The first quartile reached a UDI decrease of 60.8% with a 5-slat shading where the maximum PPD underwent a 65.2% increase. Applying a 1-slat shading worsened the occupant thermal comfort up to 8.5% compared to the base model which raised by more than triple with one more slat and boosted to 64.1% with a 3-slat shading. It should be mentioned that the median of PPD with any number of slats are between 0.8% and 22.5% increment.

While in with shadings more than two slats 25% of the outcomes saw an 8.8% increment in the EUI, the minimum reduction of this objective is achieved by 8.2% and the maximum by 34.5% with 5-slat shading. Increasing the number of slats from one to two, reduced the second quartile (75% of the outcomes) of the EUI from 2.7% reduction compared to the base model to 7.9%, followed by 11% with 3-slat shading.

3.2. *Configuration 2: Office room with two windows*

In Configuration 2, the same office room studied with two similar windows and similar shading configuration on both of them on the south and west orientation to consider the two-façade room condition.

3.2.1. *Shading slat angle*

According to Fig. 6, having a shading device with any angle simultaneously on both southern (horizontal) and western (vertical) window resulted in a significant improvement in the EUI, except for 0° and 180°, and the occupant visual comfort in contrast to the occupant thermal comfort, except for the mentioned degrees. While reaching the angle of 0° (downward rotation of horizontal shading and clockwise rotation of the vertical one) resulted in better UDI, turning toward the angle of 180° positively affect the EUI and less negative impact on the PPD. It should be mentioned that the only decrement of UDI is achieved by 18.92% at the angle of 180° where the horizontal and vertical shadings are completely rotated upward and counter clockwise. A completely horizontal and vertical shading resulted in 20.14% and 55.23% enhancement of the EUI and UDI, respectively, and about 44% deterioration of the PPD. At the angle of 120°, the maximum UDI reached the lowest amount by 30.24% improvement compared to the base model while the EUI reached a steady rate for the rest by around 30% reduction. Regardless the angle of 180°, the maximum PPD also reached the lowest by 13.11% increment compared to the base model with the shading angle of 120°. On the other hand, the EUI trend by downward rotation of the horizontal shading and clock wise of the vertical one is decreasing up to the angle of 10°, reaching 31.29% reduction, and then hiked to around 1.25% increment. Despite the worsening trend of the PPD to around 55% exacerbation and then dropping to almost similar to the base model, the UDI stood about the same around 56% improvement. Interestingly, the highest maximum of UDI is achieved at the angle of 0° by 59.60% enhancement when the horizontal shadings are completely downward and the verticals are clockwise rotated.

3.2.2. *Shading depth*

Any depth of shading has a positive impact on building energy efficiency and occupant visual comfort. However, widening the shading worsen the occupant thermal comfort from about 12.61% with 0.1 m shading to around 56.60% with the widest one. 0.1 m depth of shading slat resulted in about 18.25% improvement in UDI followed by 41.96% with 0.1 m deeper slat and reaching the maximum by around 60% enhancement with the depth of 0.3 m while the second quartile of the

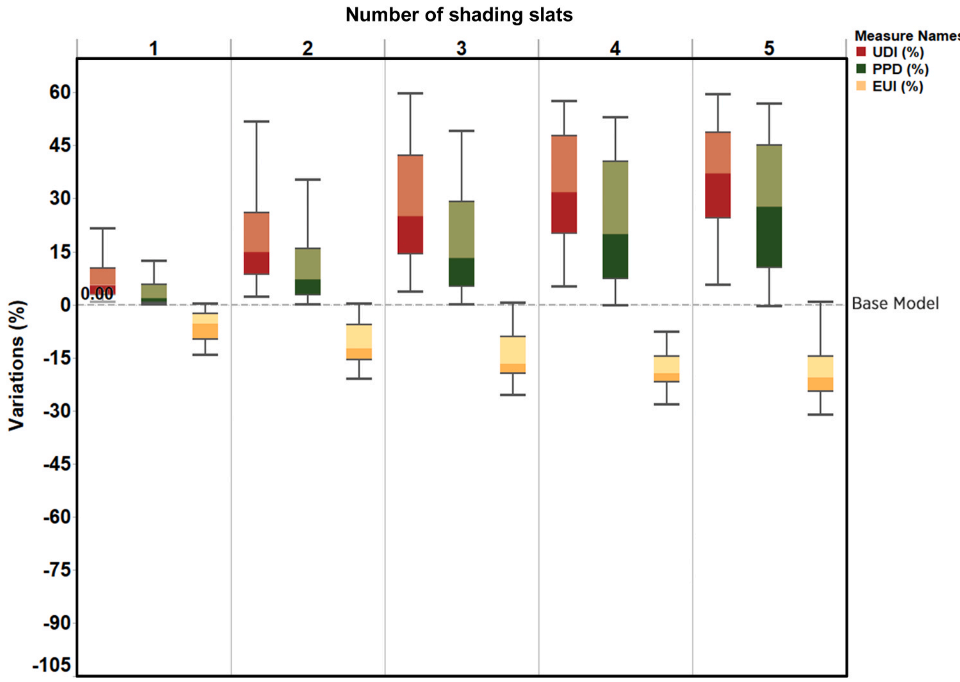

Fig. 8. The effect of the number of shading slats on EUI, UDI, and PPD in Configuration 2.

results of the latter depth are achieved by 33.59% improvement. It then stood stable around 60% where the average minimum and first quartile of UDI equal to 3% and 20% improvement compared to the base model. The improving trend of the EUI started from 14.99% reduction by 0.1 m slat shading and reached to more than 31.29% with 0.7 m one. Although with depth of shading more than 0.1 m, there is a possibility of EUI increment up to around 0.04%, the second quartile of the outcomes showed 2.40% improvement of energy efficiency (Fig. 7).

3.2.3. Number of shading slats

Similar to the other two shading variables, the EUI and UDI positively affected by adding to the number of shading devices while the occupant thermal comfort exacerbated. With a single horizontal shading on the south façade and a single one on the west façade, the maximum EUI and UDI improved by 14.29% and 21.36% and the second quartile by 2.52% and 10.27%, respectively, whereas the PPD worsened by around 12.22% with the second quartile by 5.66%. Adding one slat shading (2-slat) resulted in more than twice improvement of maximum and second quartile of UDI despite more than triple deterioration of maximum PPD with the second quartile by 15.96% aggravation. With more than 3 slats of shading device on both windows, the minimum UDI increased by around 3–5% with 5-slat one. However, the decreasing trend of minimum EUI continued to the end, reaching by more than 31.29% improvement. Interestingly, with 4-slat horizontal shading on the southern window and vertical on the western one, the minimum EUI saw around 7.86% improvement compared to the base model. On the other hand, while the minimum PPD with any number of slats are similar to the base model, the PPD maximum saw a worsening trend by adding the number of shading slat, reaching about 56.60% damage with 5-slat shading. With 2-slat shading device on both windows, the

Table 4
Specifications of the selected models.

Model number	Shading angle (°)	Shading depth (m)	Shading number	EUI (kWh/m^2)	UDI (%)	DGP	DGI	PPD (%)
Office room with one window								
1	120	0.3	5	56.66	61.16	0.26	22.63	9.33
2	110	0.3	5	55.23	69.53	0.27	23.04	9.63
3	100	0.3	4	56.22	74.53	0.27	23.01	9.76
4	110	0.4	3	57.71	71.20	0.27	22.71	9.44
5	110	0.4	4	57.06	69.57	0.26	22.69	9.60
6	100	0.4	3	57.68	74.72	0.27	23.06	9.79
7	110	0.5	3	56.29	71.24	0.26	22.72	9.58
8	110	0.5	4	56.39	68.54	0.26	22.71	9.85
9	110	0.6	3	55.36	70.90	0.26	22.71	9.76
10	110	0.7	3	55.38	69.96	0.26	22.69	9.88
Office room with two windows								
11	10	0.3	5	93.31	81.29	0.25	21.18	18.96
12	30	0.4	5	93.46	78.20	0.24	20.32	19.22
13	170	0.5	5	89.12	77.03	0.25	22.51	18.52
14	50	0.5	5	94.69	77.87	0.24	19.45	19.24
15	20	0.5	4	93.21	79.11	0.25	20.83	19.16
16	170	0.6	5	85.17	74.97	0.25	22.35	18.91
17	160	0.6	5	89.15	74.72	0.25	21.99	18.30
18	10	0.6	3	93.01	80.89	0.25	21.31	19.00
19	20	0.7	3	93.14	79.27	0.25	21.06	19.13
20	10	0.7	3	91.91	80.09	0.25	21.24	19.17

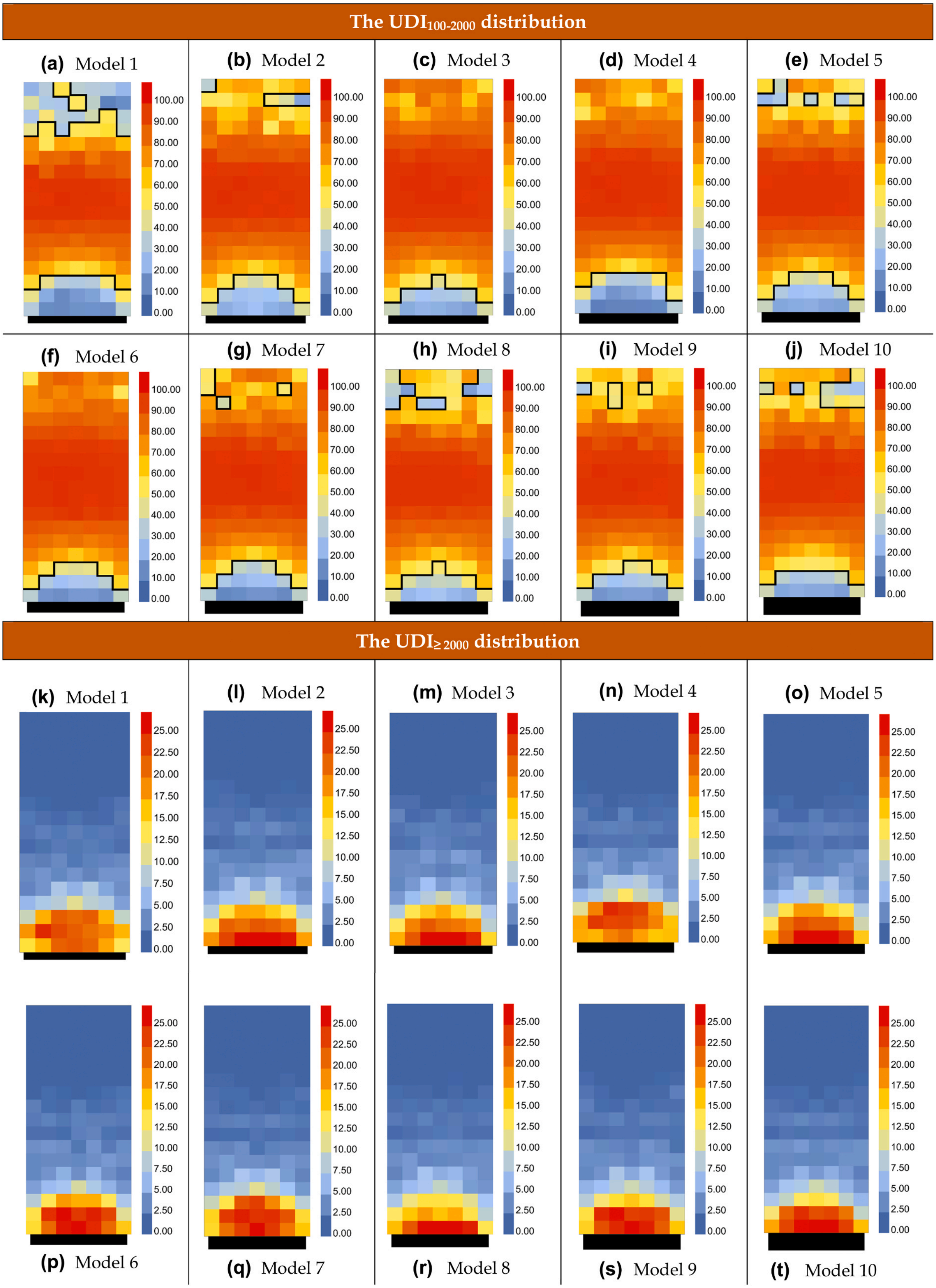

Fig. 9. Daylight distribution in Configuration 1.

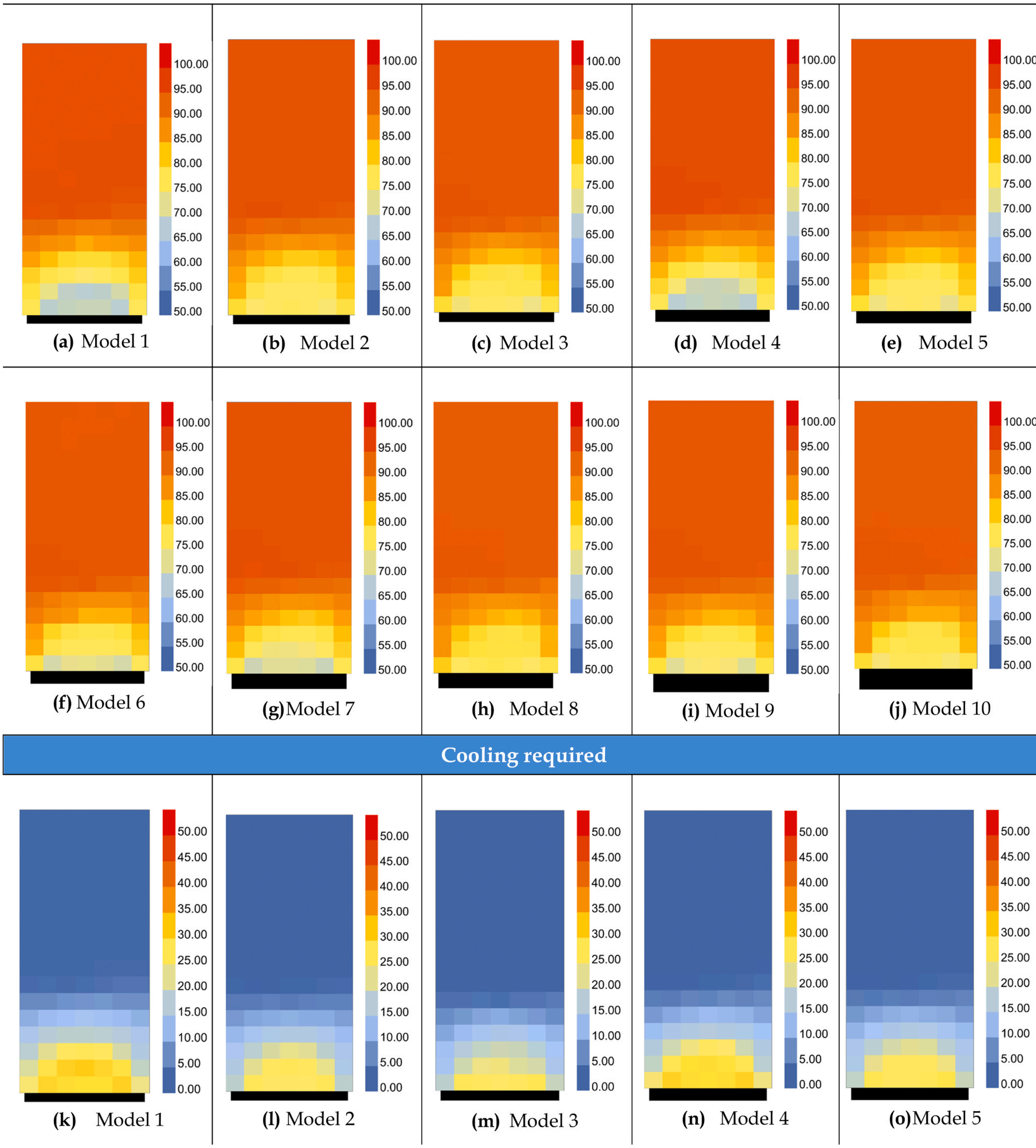

Fig. 10. Thermal comfort in Configuration 1.

maximum PPD is achieved by 35.17% increment while with having one more slat, the maximum reached 48.97% and the second quartile raised to almost twice by 30%. It then saw a slight increase to the mentioned PPD for 5-slat shading. .

3.3. Selected models

Among 1330 evaluated models, 20 models with less than 10% differences in the outcomes were selected as the selected models whose specifications are summarized in Table 4. From all studied shading angles in Configuration 1, only 100–120° can be seen in the selected options with the majority of the angle 110°, which shows that it is better to use complete horizontal or slightly upward rotated slats. The slats depth has the widest range among the assessed parameters, varying between 0.3 and 0.7 m. This feature provides architectures with sufficient flexibility in choosing the shading depth based on their design. As it can be seen, while the DGP and DGI are limited between 0.26 and 0.27 and 22–23, respectively, the UDI increases from 61.16% to 72.72% by

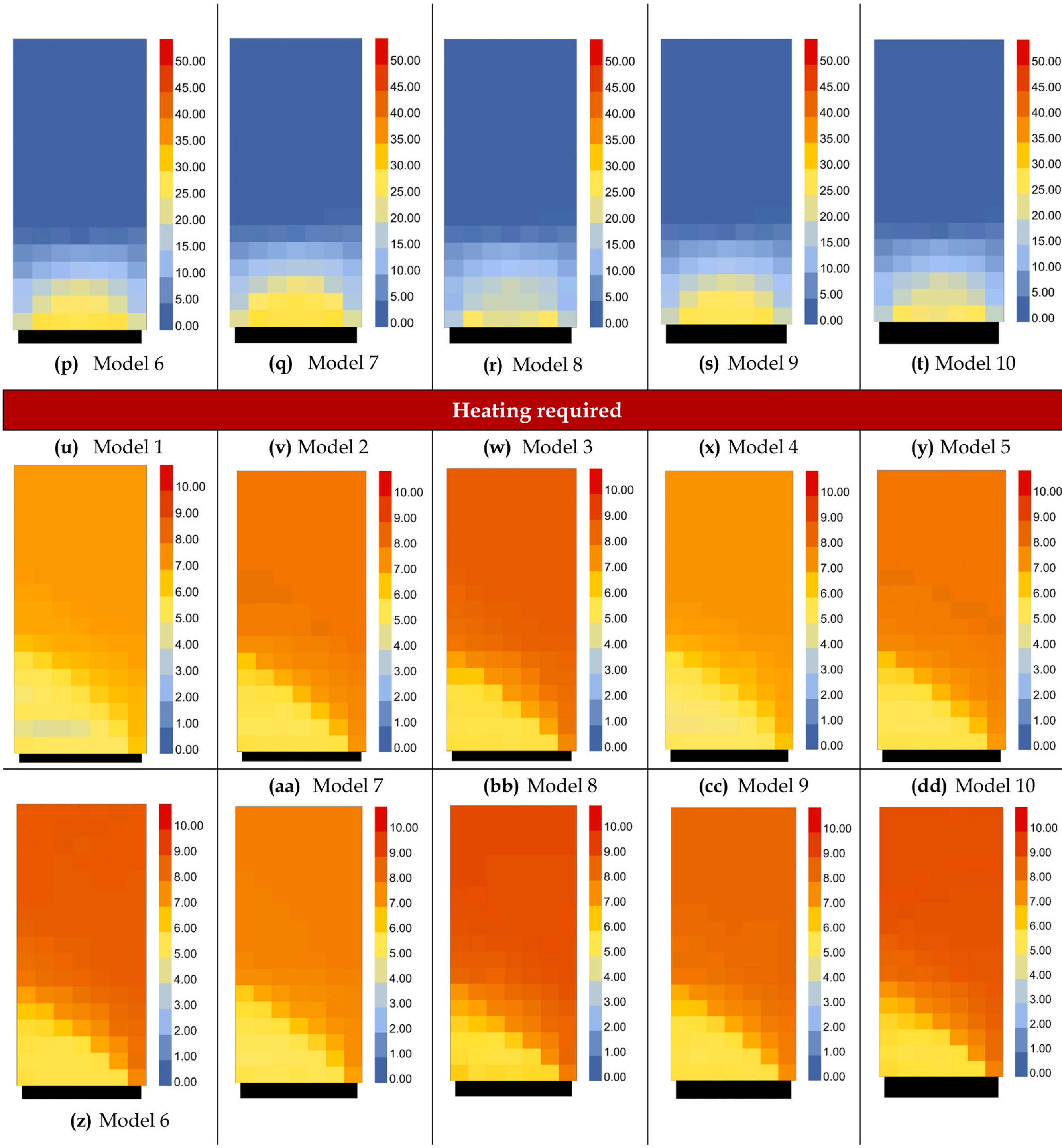

Fig. 10. (*continued*).

extending the depth of slats from 0.3 to 0.4 m. In this case, EUI and the PPD raise slightly from 56.66 to 57.68 kWh/m^2 and 9.33–9.79%. In contrast, the maximum EUI and PPD are 57.71 kWh/m^2 and 9.88% at the depths of 0.4 m and 0.7 m, respectively. Regarding the number of shading slats, three to five slats are suggested in the selected models. It is suggested to select a deeper shading more than 0.4 m when the number of slats are less than four.

In contrast to the narrow shading angles in selected models in Configuration 1, the acute angles are performed better in Configuration 2, including 10–30°, 50°, 160°, and 170° with the majority of 10° and 20°. Similar to Configuration 1, various shading depth more than 0.3 m can be selected to have a good trade-off between energy efficiency and occupant comfort. Also, the number of shading of the selected model in Configuration 2 are similar to Configuration 1, from 3-slat to 5-slat; however, 3-slat shading only performed well when the shading depth is more than 0.6 m. Regarding the objectives, the EUI and occupant thermal comfort in Configuration 2 is significantly worse than Configuration 1 while the visual comfort, including the UDI, DGP, and DGI is improved. The lowest EUI and PPD among the selected model are achieved by 85.17 kWh/m^2 with 5-slat 0.6 m depth of shading at the angle of 170° and 18.30% with the similar shading configuration with 10° less of rotation, the highest UDI is obtained by 80.89% with 3-slat shading at

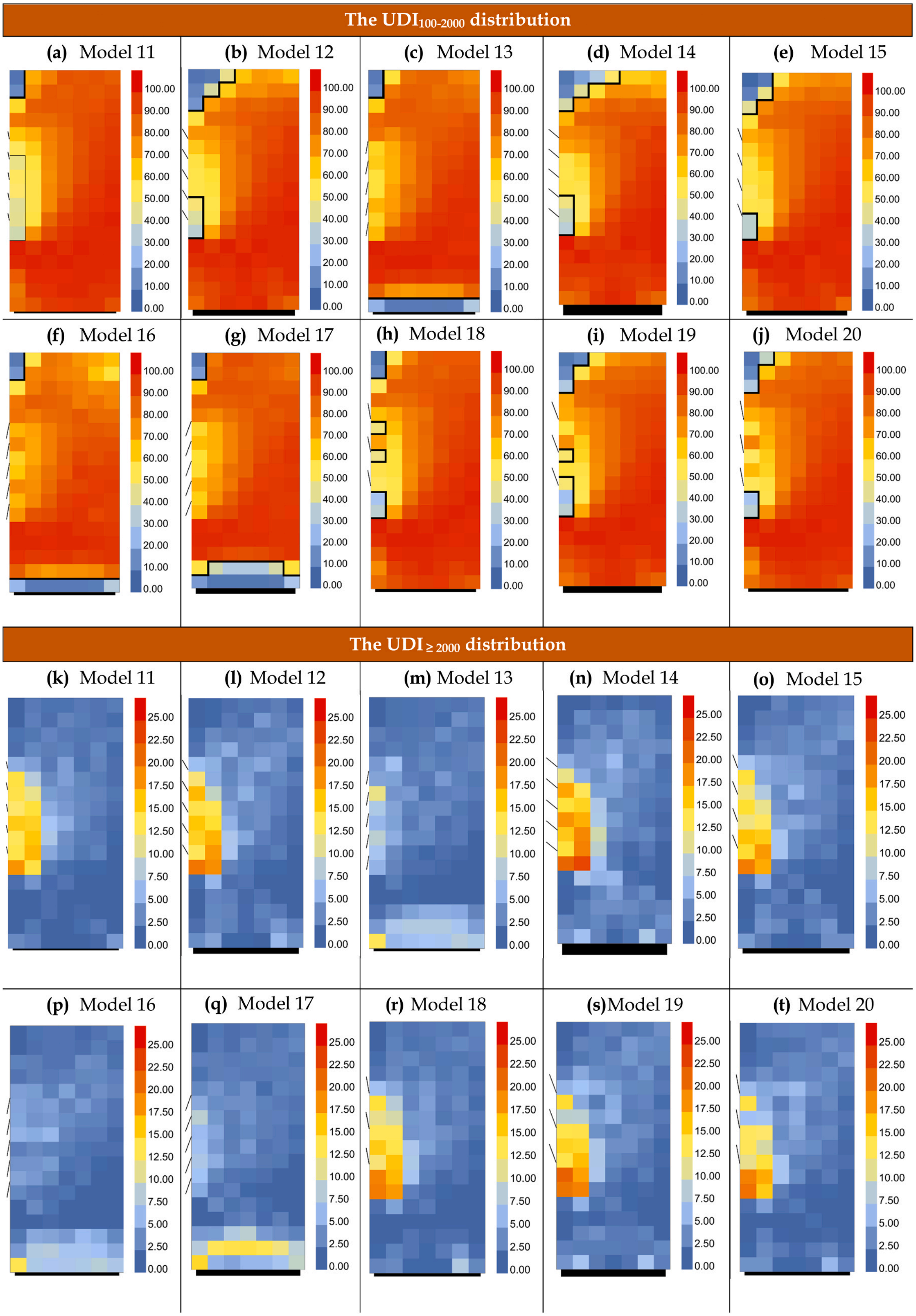

Fig. 11. Daylight distribution in Configuration 2.

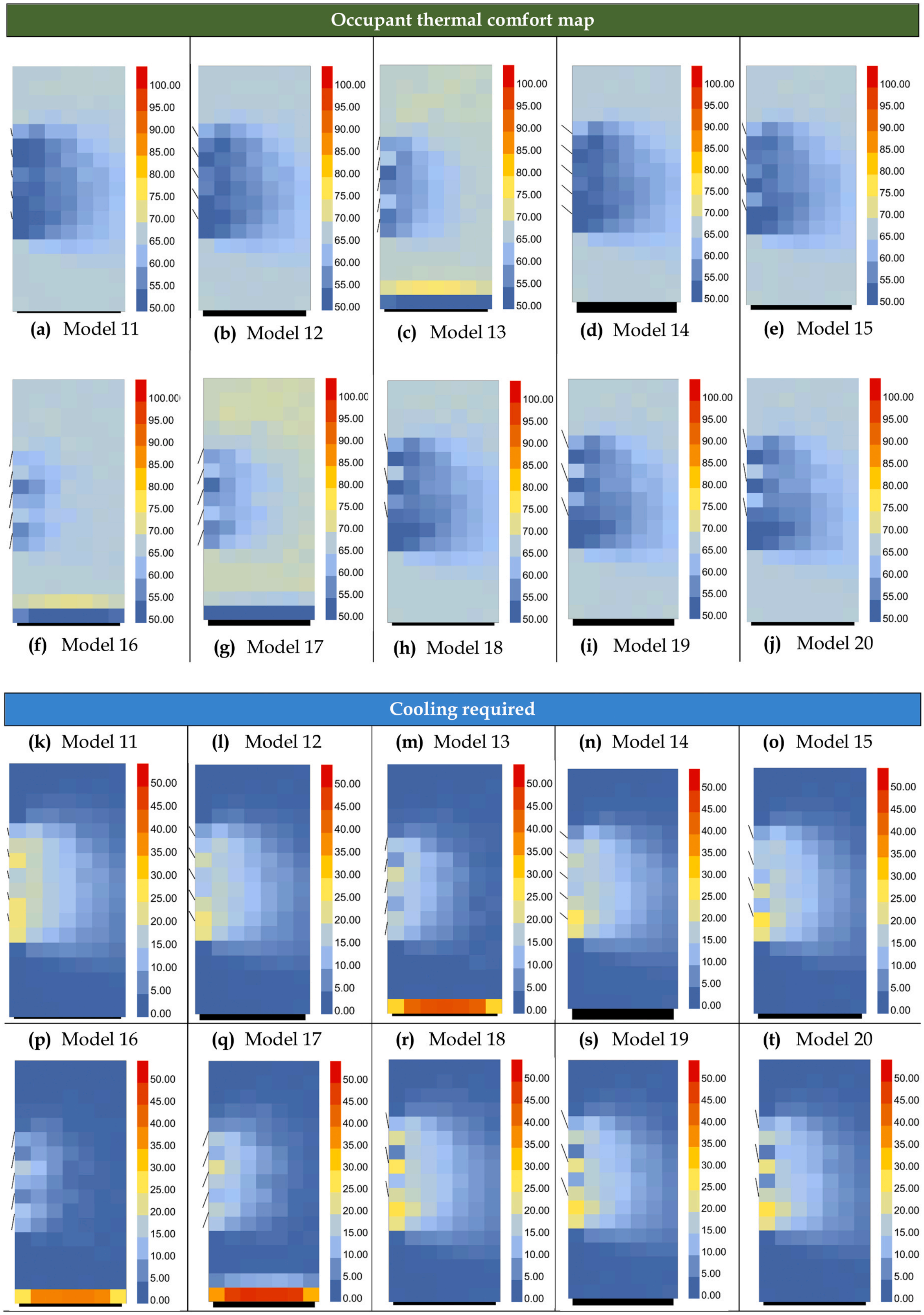

Fig. 12. Thermal comfort in Configuration 2.

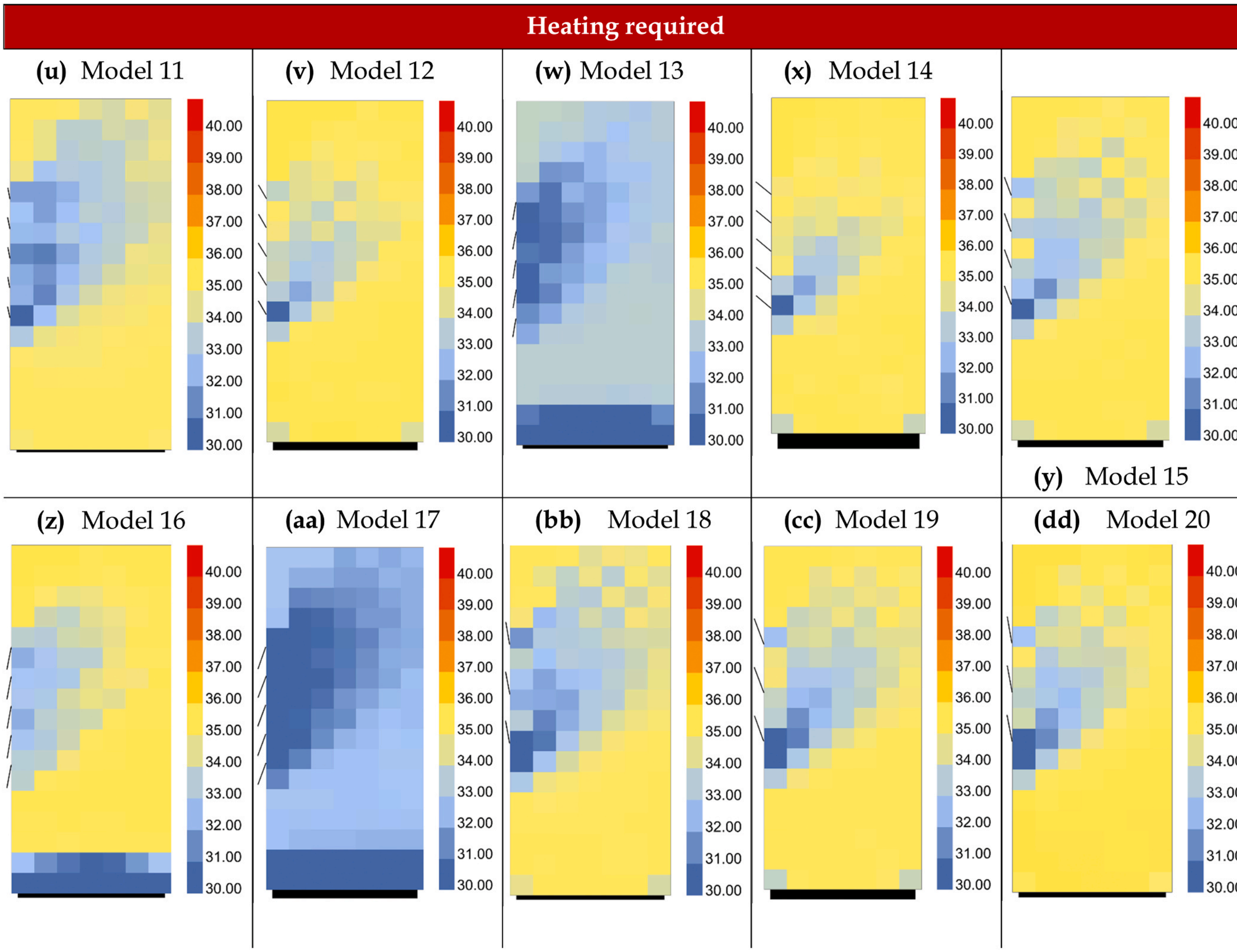

Fig. 12. (*continued*).

the angle of 10° and similar depth. On the other hand, the highest EUI and PPD equal to 94.69 kWh/m^2 and 19.24% with 5-slat 0.5 m depth of shading and 50-degree rotation while the lowest UDI equals to 74.72% with 5-slat shading rotated to the angle of 160° with 0.6 m of depth.

3.3.1. Occupant comfort in Configuration 1

According to Fig. 9, almost all parts of the room in Configuration 1 with selected shading properties received the desired $UDI_{100–2000}$ in more than half of the year, providing occupant visual comfort, except for about the 2 m near the window which experienced more excessive $UDI_{2000–3000}$ up to 25% of time in a year. Back part of the selected model number 1 required the artificial lighting in less than half of the year while the selected models 3, 4, and 6, all parts of back of the room are lit enough with daylight in more than 70% of a year, which can significantly decrease the lighting energy consumption. However, only the middle part of the room (about one third) with selected shading design received the desired daylight in all around the year.

Nevertheless, about the first 2 m near the window may experience glare by receiving the $UDI_{2000–3000}$ up to 25% of a year. In all models, except model number 1 and 8, the mentioned area received the excessive daylight in about all the mentioned time (25%). However, all the first 2 m near the window in model 1, experienced the extreme daylight by similar percentage of time around 20%. While the first 50 cm near the window in model 8 received the excessive daylight in 25% of year equal to a season, the next 1.5 m exposed to this amount by about 10% of the time or less (Fig. 9).

Fig. 10 shows the occupant thermal comfort in Configuration 1. It can be seen that occupant thermal comfort can be achieved in almost all parts of the room of all the selected models in more than half of the year while more than half of the room is in the comfort condition in more than 80% of a year. However, half of the models have a better thermal comfort even near the window for more than 75% of a year, including models 2, 3, 5, and 8–10. The area near the window in all models required cooling equipment up to half of the year regarding the received radiation. This requirement in model 8 is limited to less than 15% of a year while in other models it may exceeds up to 30% of a year. However, there is also heating requirement in the office room for a time up to 8% of the year, especially in the northern half of the room. Models 3, 6, 8, and 10 are those in which there is a heating requirement for more time than the others in contrast to the less requirement of the model 1 which shows a good thermal condition for more than half of the year.

3.3.2. Occupant comfort in Configuration 2

According to Fig. 11, the model 11 is the most lit room in more than half of the year among all of the selected models and only the north-west cornet lack of the desired daylight. This model performed an appropriate daylight distribution and most of the room are lit enough in more than 70% of a year, significantly reduce the lighting energy consumption. However, all the selected models in Configuration 2 received the $UDI_{100–2000}$ in almost all parts of the room for more than half of the year, except for the first 50 cm near the southern window of the three models of 13,16, and 17 and the first mentioned area near the western window

Table 5
Summary of the main conclusions of the study.

Parameter	Configuration 1	Configuration 2
Shading angle	• The maximum $UDI_{100-2000}$ improvement equals 12.1% is achieved with a completely horizontal shading while the EUI is reduced between 7.9% and 29%. The maximum PPD, on the other hand, raised by 56.7%. • Both downward and upward rotations up to 20° can positively affect the occupant visual comfort by increasing the desired UDI up to 9.8%, depending on the other variables, at the angle of 110° (20° upward). • Shading angle of 110° resulted in between 3.3% and 34.5% EUI reduction.	• Lowest amount of maximum UDI and PPD are achieved by 30.24% improvement and 13.11% deterioration at the angle of 120°, respectively. • The highest UDI by 59.60% is achieved with a completely horizontal and vertical shading. The highest improvement in EUI by 31.29% is at the angle of 10°. • The only decrement of UDI is achieved by 18.92% at the angle of 180°.
Shading depth	• The maximum improvement in UDI by 12.1% can be achieved with 0.6 m depth of shading while the 0.7 m depth can result in the maximum reduction of the EUI and 65.2% increment of the PPD.	• The maximum UDI improvement by 60% is achieved with 0.3 m depth of shading while the maximum EUI reduction by 31.29% is with the widest slat. • The PPD saw an increment from 12.61% to 56.60% with 0.1 m depth of shading and 0.7 m.
No. of shading slats	• The maximum raise in the UDI is occurred with 4-slat shading. • 5-slat shading may increase the PPD by 65.2% while it is limited to 8.5% with 1-slat shading. Also, the highest EUI reduction by 34.5% is achieved with 5-slat shading.	• Increasing the number of slats from one to two resulted in twice improvement of the UDI and triple aggravation of the PPD. • The maximum PPD increment by 56.60% is occurred with 5-slat shading. • The minimum improvement of the EUI equals 7.86% is obtained with 4-slat shading while the maximum equals 31.29% is achieved with 5-slat one.
Selected models	• The angles of 100–120° have a better performance regarding the building energy efficiency and occupant comfort while the shading depth vary between 0.3 and 0.7 m. Although any number of slats more than three is suitable, the fewer number should be used with a deeper shading than 0.4 m.	• Acute angles of 10–30°, 50°, 170° and 180° are suitable when having two windows on the south and west orientation. Similar to Configuration 1, the number of slats and depth vary between 3 and 5 and 0.3–0.7 m. However, 3-slat shading is better to be chosen only with slats deeper than 0.6 m.
	• While Configuration 2 proved a better occupant visual comfort, thermal comfort is better in Configuration 1.	

for models 12, 14, 15, and 18–20. In all models, southern part of the room can use the desired daylight in more time than the northern part; however, the model 16 experienced the less amount of time receiving the $UDI_{100-2000}$ than the other models.

Interestingly, in Configuration 2, only the first 1 m near the western window experienced the excessive daylight for a time up to 25% of the year in all models, except for three models of 13, 16, and 17. Almost no parts of the models 13 and 16, received the $UDI_{2000-3000}$ more than 10% of a year and only a small southern part of the model 17 received the mentioned UDI for about 12% of a year (Fig. 11).

Regarding the occupant thermal comfort. Fig. 12 shows that it can be achieved in almost all the selected models for less than 70% of the year, especially in middle part of the room, and it diminishes to less than half of the year for in the area near both windows, except for the model 13 and 16. Some of the northern and southern parts of the room in models 13 and 17 are under the thermal comfort condition for between 70% and 75% of the year while it is almost less than 65% for the other models. However, the area near the window required cooling for up to 25% of the year, especially for the first 50 cm near the southern window in the models 13, 16, and 17 which increased to up to half of the year. The minimum cooling required time in the middle part of the area in the first 50 cm near the southern window the model 17 equals to 35% of a year while it limited to the maximum of 20% for the western window.

On the other hand, a vast area of the room in all the selected models in Configuration 2 required heating for about 35% of the year, except for two models of 13 and 17 which decreased to about 32%. However, the area near the southern window in models 13, 16, and 17 required less time of heating as well as the north-west part of the other models. This requirement is due to the acute angles of shading which prevent the radiation penetration, affecting the room thermal condition.

Both Configurations provided a suitable distribution of the desired daylight in all over the room for more than half of the year, resulting occupant visual comfort. However, in Configuration 1, some area in the northern part of the room required artificial lighting for a time up to 50% of the year while this area is limited to the north-west corner in most of the selected models of Configuration 2. The shading properties of the selected models of both Configurations resulted in the probability of glare due to the $UDI_{2000-3000}$. In Configuration 1, the first 2 m near the window in all of the selected models received the excessive daylight for a time up to 25% of the year while it is limited to 7 models in Configuration 2 for the first 1 m near the western window and less time which is a result of acute shading angle, resulting in less DGP and DGI simultaneous with more percentage of $UDI_{100-2000}$.

Occupant thermal comfort is better provided in the selected models of Configuration 1 with a single southern window and the selected shading device properties while when the western window is added to the office in Configuration 2 with similar shading properties to the southern one, the average thermal comfort time is decreased from 85% to 65%, almost doubling the EUI and PPD. Moreover, the area under the cooling requirement condition in Configuration 1 is limited to the first 2.5 m near the window while almost all areas in the middle of the room in Configuration 2 required heating for between 10% and 20% of the year. However, the area under heating requirement is significantly more in Configuration 2 than Configuration 1. The maximum time of heating requirement in Configuration 1 is 8%, especially in the northern half of the room while the minimum time of hearing demand in Configuration 2 equals 30% of the year with the average of 35% which is due to the acute shading angle of both windows, especially the southern one.

The distinctive aspect of this study lies in its focus on contrasting various window arrangements, as well as the comparison between rooms featuring a sole southern window and those incorporating multiple windows across multiple facades. The central outcomes and comparisons have been summarized in Table 5.

4. Conclusions

This study evaluated the effect of shading device parameters, including shading depth, number of slats, and slat angle, for a typical office room in Tehran, Iran to improve the building energy efficiency and occupant comfort. Comparing a room with a single southern window to one with multiple windows on multiple facades represents one of the primary novelties of this research. Two Configurations are studied; Configuration 1 consists of the office room with a single southern window and horizontal shading device and Configuration 2 consists of two similar windows on the south and west façades with similar horizontal and vertical shading device configuration, respectively. The shading variables are 0.1–0.7 m of depths, 1–5 no. of slats, and 0° (downward for the horizontal shading- clockwise for the vertical) to 180° (upward for the horizontal shading- counter clockwise for the vertical) slat angles were investigated. The objectives of this study were reducing the EUI and PPD, while increasing the UDI. The parametric study of 1330 models performed, using Rhinoceros Grasshopper software for modelling and Ladybug Tools for energy, daylight and thermal analysis. Finally, 20 models were selected with a better trade-off between the building energy consumption and thermal-visual comfort with less than 10% outcome differences, using Design Explorer platform.

The findings reveal that, in general, multiple deep shading systems are more advantageous for enhancing building energy efficiency and occupant visual comfort in Configuration 1. Notably, shading angles ranging from up to 20°, both upward and downward, yielded superior outcomes, with the maximum improvement in the UDI reaching 12.1%. This improvement coincided with the EUI experiencing reductions ranging from 7.9% to 29%, while the PPD increased by 56.7%. In Configuration 2, the combination of fully horizontal and vertical shading systems produced the most notable improvement in UDI, resulting in a remarkable increase of 59.60%. Interestingly, although acute angles were found to be generally more efficient for Configuration 2, the most substantial reduction in EUI, amounting to 31.29%, was achieved with an acute angle of 10°.

CRediT authorship contribution statement

Sarah Nazari: Conceptualization, Simulation, Visualization, Investigation, Validation, Writing – original draft. **Payam Keshavarz Mirza Mohammadi:** Simulation, Visualization, Investigation, Validation, Writing – original draft. **Behrang Sajadi:** Conceptualization, Supervision, Investigation, Writing – original draft. **Peiman Pilehchi Ha:** Investigation, Validation, Writing – original draft. **Siamak Talatahari:** Investigation, Writing – reviewing and editing. **Pooya Sareh:** Supervision, Investigation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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