Article

Impact of Manually Controlled Solar Shades on Indoor Visual Comfort

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Abstract: Daylight plays a significant role in sustainable building design. The purpose of this paper was to investigate the impact of manual solar shades on indoor visual comfort. A developed stochastic model for manual solar shades was modeled in Building Controls Virtual Test Bed, which was coupled with EnergyPlus for co-simulation. Movable solar shades were compared with two unshaded windows. Results show that movable solar shades have more than half of the working hours with a comfortable illuminance level, which is about twice higher than low-e windows, with a less significant daylight illuminance fluctuation. For glare protection, movable solar shades increase comfortable visual conditions by about 20% compared to low-e windows. Moreover, the intolerable glare perception could be reduced by more than 20% for movable solar shades.

Keywords: manual solar shades; indoor visual comfort; daylight glare probability; useful daylight illuminance; co-simulation

1. Introduction

Sustainable building design requires a comprehensive consideration of daylight utilization, which has improvements on view to outdoor [1], visual and psychological comfort [2], health [3], and working efficiency [4], and thus windows are considered a fundamental element of building facades. To maximize daylight and winter solar gain, contemporary buildings are designed with large windows or glazing curtain walls, which, in turn, can also lead to negative influences on the indoor environmental conditions. For example, too much daylight brings glare problems and daylight with excessive solar heat gains increases cooling energy demand. To have a balance between these aspects, solar shading devices are usually used, which can be designed to prevent overheating, to reduce heating losses and cooling loads, and to control the visual environment (glare, daylight, contrast, view towards and from the exterior).

Fixed shading devices, as a simple solution, are usually employed in the building envelope to address this need. For example, Stazi et al. [5] reported that different fixed shading devices (aluminum horizontal louvers, aluminum persiana, and traditional wooden persiana) all providing medium daylighting factors higher than the threshold value of 2% (fixed by UNI EN 15193) in a Mediterranean climate. However, there is no improvement in the light uniformity level after using shading devices, with a resulting uniformity ratio of less than 0.12, which is even a little poorer than with the no shading condition. Ahmed [6] compared three fixed shading devices (vertical fins, diagonal fins and egg crate) in terms of thermal and daylighting performance. The results showed that offices with

diagonal fins and egg crate shading devices performed better compared to the office with vertical fins. Research carried out by Cristina et al. [7] also suggested the use of shading devices as passive control systems in improving indoor thermal conditions. Esquivias et al. [8] conducted a simulation study on daylight analysis of fixed shading devices (overhangs, side fins, horizontal and vertical louvres) in an open-plan office. Their research showed that excessive obstruction may yield an excessive reduction in a range of illuminance between 500 and 2000 lux, thus increasing lighting energy consumption. Therefore, fixed shading devices are not efficient in controlling dynamic daylight illuminance.

On the other hand, movable shading devices can be adjusted in accordance with the changing outdoor conditions in order to achieve minimal energy consumption for lighting, heating and cooling while at the same time offer a comfortable visual environment. Movable shades can be classified into the manual, motorized and automated type according to the control method. Manual shades are the simplest type as they do not incorporate a motorized device. Motorized ones are operated by motors, indicating that remote or central operation is possible while automated ones are automatically controlled by sensors according to the indoor or outdoor weather conditions to enhance building performance [9]. Nielsen et al. [10] simulated the daylighting performance of automated dynamic solar shading in office buildings. Their research emphasized the need for dynamic and integrated simulations early in the design process in order to facilitate informed design decisions about the façade. Myung et al. [11] developed an automated control strategy for slat-type blind that has an optimum slat angle adjustment, by which glare can be fully removed (a glare occurrence ratio of 0.1%) and at the same time a significant energy improvement can be achieved.

For rooms with many automated blinds, occupants often adjust all of the blinds to the same position in order to keep sunlight's penetration through windows at an acceptable depth. This may lead to the blockage of useful daylight and view to outdoor. Koo et al. [12], thus, developed a new blind control strategy to make full use of daylight while preventing glare risks. This strategy can be used to control individual multiple blinds to different shading positions according to occupants' preference for the daylight distribution.

To reach the abovementioned magnitude of improvement in visual comfort performance for movable shading devices, a complex control system will be required to maintain the frequent changing of shade positions or angles. Thus, it is more expensive than manually controlled shades and the costs are even higher with maintenance. Unfortunately, manually controlled internal solar shades are widely used in office buildings in China [13]. Moreover, occupants' shade control is not as efficient as motorized systems since occupants' behavior is stochastic [13–16]. Therefore, the rigorous evaluation of the impact of manual solar shades on indoor visual comfort should account for the stochastic characteristic of occupants' behavior. This paper continues the previous research and focuses on the visual comfort (the focus of previous studies are on energy [13] and indoor thermal comfort [17]) by taking into account the stochastic adjustment of solar shades based on a co-simulation study.

2. Methodology

2.1. Case Study

The research was conducted in Ningbo (a typical city in hot summer and cold winter zone of China with 1517 heating degree days (HDD, unit: °C·d) and 89 cooling degree days (CDD, unit: °C·d)) and a typical office room model. Its dimensions are 4 m × 4 m × 3 m with a 3.8 m × 2.8 m window on the west facade. To compare the performance of movable solar shades with bare windows in terms of daylighting and glare protection, four window settings were considered. The first two scenarios (clear double-pane windows and low-e double-pane windows) are the most popular design measures in this climatic region where movable solar shades are not mandatory design measures. The other two scenarios represent interior and exterior movable solar shading devices, respectively. For modeling movable solar shades, two equal solar shades side by side (Shade1 and Shade2, either of which can be placed inside the window (Shadeint) or outside (Shadeext)) were considered and each of them can be

controlled independently, as shown in Figure 1. The characteristics of the office room and the four scenarios are shown in Table 1. The material property of roller solar shades was collected from a local manufacturer. It should be mentioned that the last two parameters (Computer screen luminance and Sky condition) are only used to calculate the Daylight glare probability index described in Section 2.3 while other performance was simulated by EnergyPlus by considering all sky conditions for the whole year (8760 h).
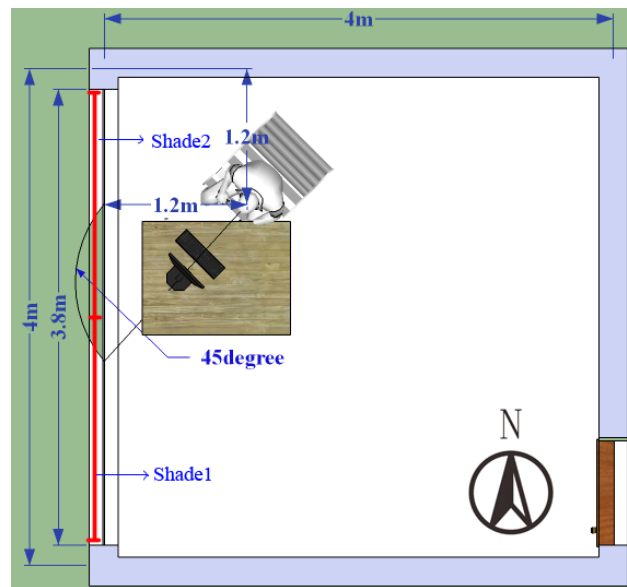

Figure 1. Room model plan showing the occupant position with movable solar shades [17].

Table 1. Characteristics of the office room.

Parameter	Value
Location	Ningbo city, latitude: 30°, longitude: 120°
Room orientation	West
Dimension	Room: 4 m × 4 m × 3 m, Window: 3.8 m × 2.8 m
Window and shading device	Four window settings for comparison: (1) CL: Clear double-pane windows, visual transmittance: 0.89; (2) LOW-E: Low-e double-pane windows, visual transmittance: 0.69; (3) Shadeint: Clear double-pane windows + manually controlled internal solar shades, shade material property: visual transmittance: 0.2 (beam: 0.04, diffuse: 0.16), reflectance: 0.7 (Specular: 0; diffuse: 0.7); roughness: 0.01; (4) Shadeext: Clear double-pane windows + manually controlled external solar shades, shade material property: visual transmittance: 0.2 (beam: 0.04, diffuse: 0.16), reflectance: 0.7 (Specular: 0; diffuse: 0.7); roughness: 0.01
Surface reflectance	Wall: 0.75, ceiling: 0.75, floor: 0.25
Electric lighting	2 T8 fluorescent
Occupant view direction	45° south by west
Computer screen luminance	100 cd/m^2
Sky condition	Intermediate sky with sun

2.2. Co-Simulation for Movable Solar Shades

The simulation tool EnergyPlus, which is developed by the U.S. Department of Energy (DOE) [18], was used to carry out the visual performance simulation for the first two design measures (CL and LOW-E). A software environment for co-simulation named Building Controls Virtual Test Bed (BCVTB) developed by Lawrence Berkeley National Laboratory [19] was used for co-simulation with EnergyPlus for the other two measures (Shadeint and Shadeext) since the developed stochastic model for movable solar shades cannot be simulated by EnergyPlus alone. Although this paper is a simulation based study, the reliability of the co-simulation conducted has been validated based on field measurement [13].

To investigate the impact of shade control behavior on visual comfort, the shade control model developed by the author [13] and the same solar shades were used in this paper. The model was developed based on long term field measurements during three seasons and the cumulative odds logit model was used for calculationin order to identify the main factor in influencing shade control.

Since using 5shade positions is adequate and reasonable for simulating building performance [20], shade deployment was divided into 5 positions (cover window area of 0%, 25%, 50%, 75% and 100%, respectively). Then the time-constant Markov chain method was adopted to construct the stochastic model of shade control behavior, and the Markov chain transition matrix for different sky conditions were calculated and classified according to the driving factor.

To reflect occupants' behavior characteristics under different sky conditions, four transition matrices were constructed based on the threshold of receiving direct solar radiation (the driving factor) for each season as follows: (1) continuously without direct solar radiation; (2) from without direct solar radiation to receiving it; (3) continuously receiving direct solar radiation; and (4) from receiving direct solar radiation to without it. Thus, a total of 12 Markov transition matrices for occupants' shade control were considered for the three seasons (summer, winter and transition seasons). The values in each matrix were determined by counting the shade changing behavior during the corresponding measurement period, which represent the probabilities of solar shade adjusted from one position to another. For example, the Markov chain transition matrix for west solar shades in summer for the first sky condition (continuously without direct solar radiation) is shown in Table 2. It can be seen that if a solar shade at a position of 25% at the current time step, then the probability for this shade kept unchanged at the next time step is 77% and it is only 3% for the shade to be adjusted to 0% position, 8% to 50% position, 10% to 75% position and 2% to 100% position. Similarly, the probabilities of shade adjustment at other positions under other conditions (all other Markov chain transition matrices) have been determined and listed in paper [13].

Then, this Markov model for solar shades was modeled in BCVTB for co-simulation with EnergyPlus. At each time step, BCVTB will check the solar radiation intensity on external windows from EnergyPlus and then randomly generate a shade position according to the probability distribution listed in corresponding Markov chain transition matrix and this shade position will then be applied in EnergyPlus simulation. Beside the position difference, both internal and external solar shades are manually controlled in this paper and thus the same Markov matrices are used for co-simulation.

Table 2. Markov chain transition matrix for west solar shades in summer for the first sky condition (continuously without direct solar radiation).

		Next Solar Shade State				
		0%	25%	50%	75%	100%
	0%	0.76	0.03	0.09	0.08	0.04
	25%	0.03	0.77	0.08	0.10	0.02
Current solar shade state	50%	0.04	0.07	0.82	0.06	0.01
	75%	0.05	0.1	0.05	0.75	0.05
	100%	0.06	0.09	0.11	0.06	0.68

The developed shade control model is based on long-term field measurement, reflecting the occupants' real shade control behavior, thus it is relibale. A brief description of how this model is developed and simulated in BCVTB can be seen in Figure 2. More information about this model can be found in paper [13].
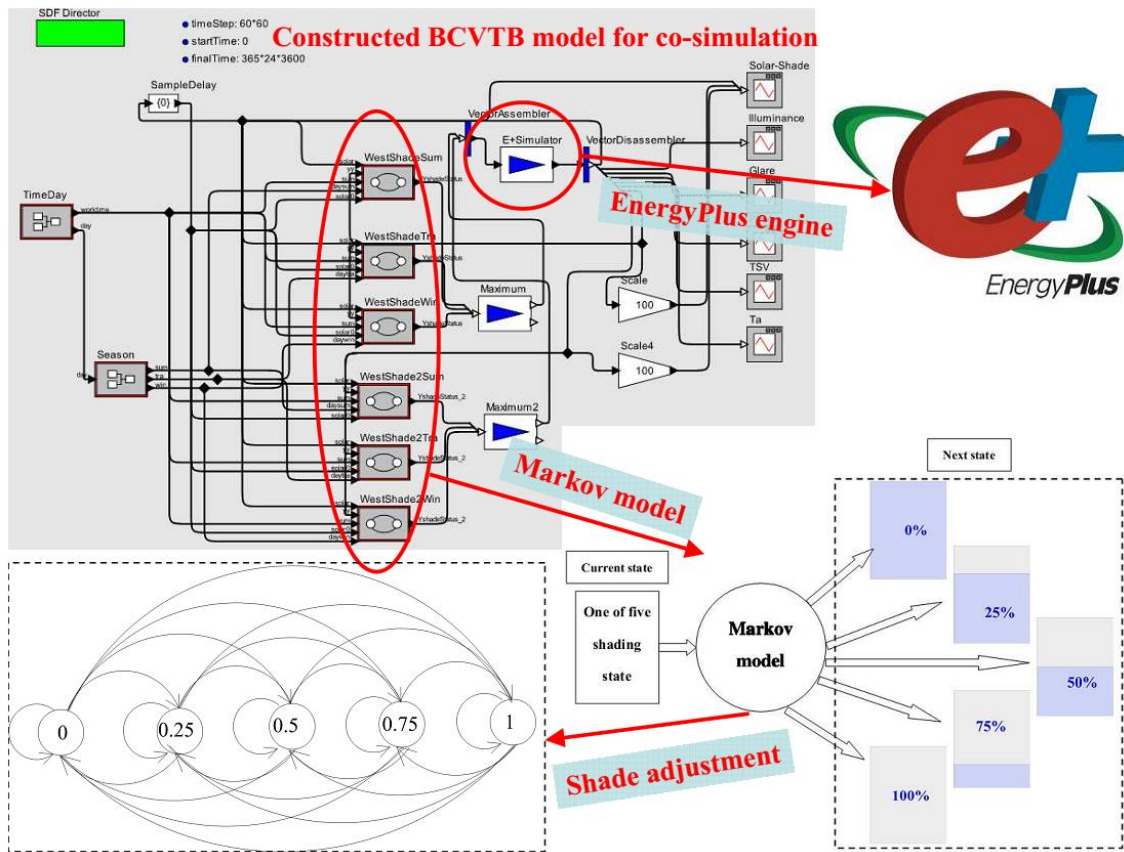
Figure 2. A graphic illustration of the developed method for co-simulation of the performance of manual solar shades.

2.3. Analyze Index

To have a comprehensive evaluation of indoor visual comfort, several indices have been adopted to assess the daylighting and glare protection performance. These indices include useful daylight illuminance (UDI), daylight illuminance fluctuation (DIF), daylight glare index (DGI), and daylight glare probability (DGP).

2.3.1. Useful Daylight Illuminance

As a quantitative index, useful daylight illuminance (UDI) can be used to evaluate the daylighting performance [21]. According to UDI index, it can be determined that when daylight levels are not too dark for the occupant (more than 300 lux, otherwise additional electrical lighting is needed) [22] and not too bright (less than 2000 lux, otherwise glare risks may occur) [21].

2.3.2. Daylight Illuminance Fluctuation

Daylight illuminance varies with sky conditions and a significant fluctuation of illuminance has a negative impact on indoor visual comfort and occupants may feel too bright or too dark during this change. Therefore, fluctuation of daylight illuminance is also an important factor in influencing occupants' visual perception, and, in theory, the smaller the better. At present, there is no equation or index for calculating daylight illuminance fluctuation (DIF) and thus the authors have introduced the standard deviation as the evaluation index. This can be expressed as follows:

$$E_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(E_i - E_{ave}\right)^2} \tag{1}$$

where E_σ is the standard deviation of daylight illuminance, N is the daytime working hours (10 h), E_i is the daylight illuminance of ith working hour and E_{ave} is the average daylight illuminance of the working hours for a day as shown below.

$$E_{ave} = \frac{1}{N}\sum_{i=1}^{N} E_i \tag{2}$$

2.3.3. Daylight Glare Index

Glare is a measure of the physical discomfort that may be caused by excessive light or contrast in a field of view [23]. Daylight Glare Index (DGI) is an index for the evaluation of the magnitude of discomfort glare experienced from windows. DGI depends on the physical factors such as the luminance values of the light sources, background and window, the solid angle subtended by the source, and the solid angle subtended by the window. The first expression of DGI (the "Cornell formula" [24]) was derived from the BRS formula. The original equation has been later modified by Chauvel [25] as follows:

$$DGI = 10\log_{10} 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \Omega_s^{0.8}}{L_b + 0.07\omega_s^{0.5}L_s} \tag{3}$$

where L_s is the luminance of the source (cd/m^2), L_b is the background mean luminance (cd/m^2), Ω_s is the solid angle of the source (sr) and ω_s is the solid angle subtended by the window (sr).

2.3.4. Daylight Glare Probability

Based on the vertical eye illuminance levels and other glare source parameters, Wienold and Christoffersen developed daylight glare probability (DGP) index [26]. Compared to other glare indices or models, DGP shows a better performance in reflecting occupants' glare perception. It can be calculated according to the following equation:

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log(1 + \sum_i \frac{L_s^2 \cdot \omega_s}{E_v^{1.87} \cdot P_i^2}) + 0.16 \tag{4}$$

where E_v is the vertical illuminance at eyelevel (lux) and P_i is the Guth position index. The relationships between glare perception and DGI and DGP scores [27] are shown in Table 3.

Table 3. Degree of glare in different glare indices.

Index	Glare Perception			
	Imperceptible	Perceptible	Disturbing	Intolerable
DGI	<18	18–24	24–31	>31
DGP	<0.35	0.35–0.4	0.4–0.45	>0.45

2.4. Calculation of Analyzed Index

EnergyPlus is a powerful building performance simulation engine and it is capable of simulating daylighting and glare performance. Thus, UDI, DIF and DGI are simulated by EnergyPlus (or co-simulation by EnergyPlus and BCVTB for movable solar shades) or manually calculated according to the simulation output (UDI and DIF are further manually counted). These indices are simulated/calculated at occupant's sitting position as shown in Figure 1 (UDI and DIF with a working plane height of 0.8 m while DGI with occupant view direction shown in Table 1). However, DGP is a newly developed index and has not been included in EnergyPlus simulation. Hence, it is calculated by a tool named Evalglare, developed by Wienold [26].

Evalglare uses images in the Radiance image format (PIC or HDR) which enables its user to evaluate simulated scenes as well. Thus the scenes of the room model with the four measures are simulated in Radiance, a widely used software for daylighting simulations [28], and the PIC format images are created. For movable solar shades, there are 25 scenes (five shade positions for each solar shade and thus a total of 5×5 scenes) for Shadeint/Shadeext. Each scene is simulated for different seasons and daytimes (working hours are from 8:00 to 17:00) and three typical days in each season is considered (summer: 1 July, winter: 1 January, and transition season: 15 April) in each season (summer: from 1 June to 30 September, winter: from 1 December to 28 February and transition season: from 1 March to 31 May and from 1 October to 30 November) [17], due to a prohibitively time consuming simulation in Radiance (the simulation of one scene is about 0.5 h and thus it would require a total of 91,250 h ($0.5 \times 3650 \times 25 \times 2$) to simulate the whole year for the two movable solar shades hour). Due to the fact that the penetration of sunlight at different days in the same season does not change considerably, this assumption is therefore reasonable [17].

Then the PIC format images for each scene at each time are used in Evalglare for glare scores (DGP) evaluation and the detected glare sources will be colored (the rest is automatically in grayscale, different colors). When evaluating glare intensity, a task luminance (a circular zone on center of the computer screen reflecting occupants' computer tasks) is considered as threshold for the glare source detection. The advantage of using task luminance is that it takes into account the adaption of occupants' eyes compared to a fixed luminance threshold value of 2000 cd/m^2. The different colors indicate separate glare sources and no special meaning of the color exists in Evalglare version 1.08. Each pixel in the scene with a luminance value 10 times higher than the average task-zone luminance is treated as a glare source.

3. Results and Discussion

3.1. Useful Daylight Illuminance

Figure 3 illustrates daylight illuminance for the four scenarios during annual working hours. It can be seen that CL and LOW-E have more hours with high daylight illuminance compared with Shadeint and Shadeext. The daylight illuminance was further categorized into three components (<300, 300–2000 and >2000) as shown in Table 4 in order to have a detailed comparison. Shadeext has a total UDI of 2024 h (corresponding to a 55.45% of working hours), followed by Shadeint (1942 h, 53.21%) and LOW-E (976 h, 26.74%), while the poorest measure is CL (813 h, 22.27%). This means that movable solar shades perform better than LOW-E and CL by approximately 100% in terms of UDI. Although movable solar shades have a small negative impact, with more hours of daylight illuminance less than 300 lux, their positive impact of reducing potential glare risk is more significant with a reduction of daylight illuminance higher than 2000 lux by more than 1000 h. It can also be seen that the daylight illuminance of more than 30 klux occurs in Figure 3c,d, indicating that the shading device does not shade the direct sunlight. This is because solar shading devices considered in this paper are manually adjusted based on occupants' stochastic control (does not always effectively control shading devices) and there is a probability (see Markov matrices described above) that shading devices will be kept unused even if direct sunlight penetrates into the room.

Table 4. Daylight illuminance distribution.

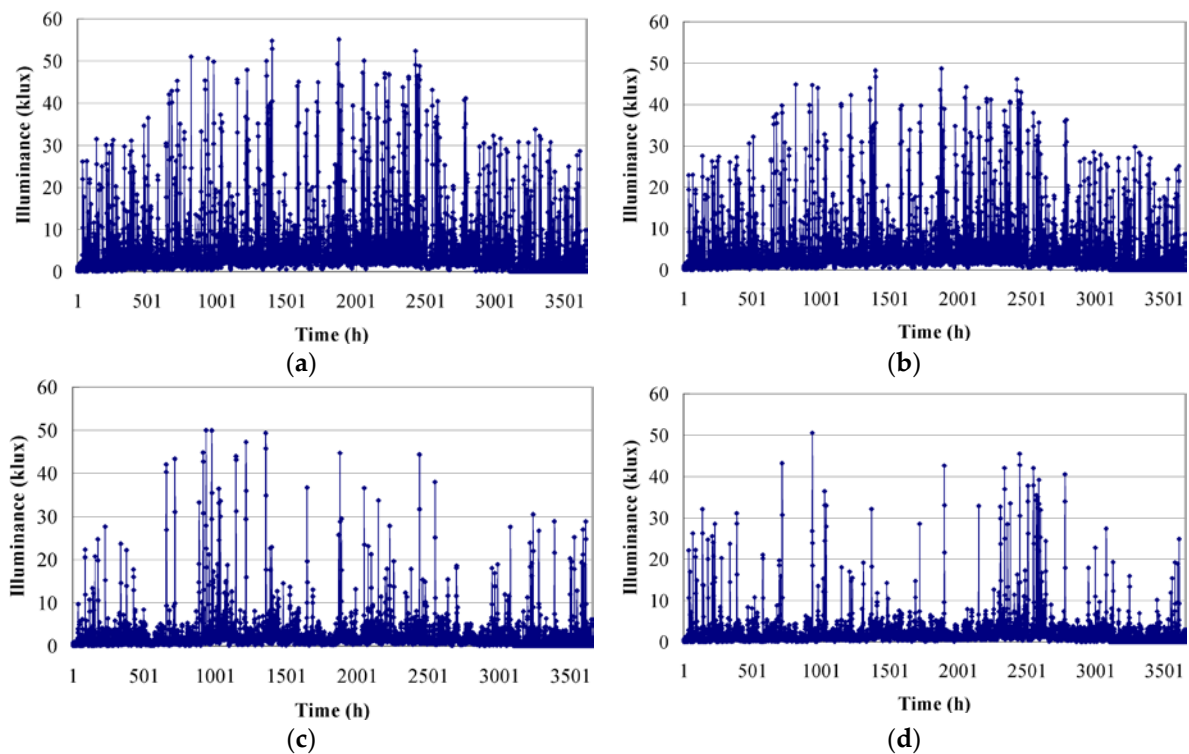|	Daylight Illuminance (lux)	CL	LOW-E	Shadeint	Shadeext
Hours	<300	90	93	253	281
	300–2000	813	976	1942	2024
	>2000	2747	2581	1455	1345
Percentage	<300	2.47%	2.55%	6.93%	7.70%
	300–2000	22.27%	26.74%	53.21%	55.45%
	>2000	75.26%	70.71%	39.86%	36.85%

Figure 3. Daylight illuminance for the four scenarios during annual working hours. (**a**) Cl; (**b**) LOW-E; (**c**) Shadeint; (**d**) Shadeext.

3.2. Daylight Illuminance Fluctuation

Figure 4 shows daily average daylight illuminance for the four scenarios. It can be seen that CL and LOW-E are both higher than 5000 lux, while Shadeint and Shadeext are only about 2600 lux. Therefore, the average illuminance of movable solar shades is more suitable for indoor occupants since it is not too bright compared with bare windows (CL and LOW-E) according to the UDI range.

For daily standard deviations of daylight illuminance, movable solar shades also perform better than CL and LOW-E with only about half of illuminance fluctuation as shown in Figure 5. The main reason for the higher of movable solar shades in terms of UDI and DIF is that solar shades can be manually controlled by occupants in response to changing outdoor conditions. Consequently, daylight illuminance on the working zone will be maintained at a relatively comfortable level. An example of occupants' shade control on shades with an improvement of daylight illuminance level is shown in Figure 6. Shadeint has a daylight illuminance of about 2000 lux while it is higher than 5000 lux for CL at occupant's sitting position. Moreover, the annual average daylight illuminance approaches more to the comfort region than the other two measures with less fluctuation, as can be seen in Table 5. Figure 7 further gives the distribution and cumulative percentage of daylight illuminance for the four scenarios. It can been seen that daylight illuminance mainly distributes in the range of 300–4000 lux for movable solar shades while the fluctuation of daylight illuminance for bare window and LOW-E have are more significant, mainly ranging from 300 to >10,000 lux. Therefore, from the point view of DIF, movable solar shades are better than bare windows and LOW-E windows.

For movable solar shades, Shadeext performs a little better than Shadeint in terms of UDI and DIF. This means that external solar shades do not necessarily block excessive daylight to an extent that would lead to a poorer performance compared to internal shades. Instead, external shades could keep indoor daylight levels at a comfortable region (see Table 5) with a 2.24% improvement relative to internal ones. Thus, it is better to use external solar shades even if a daylighting purpose is considered.
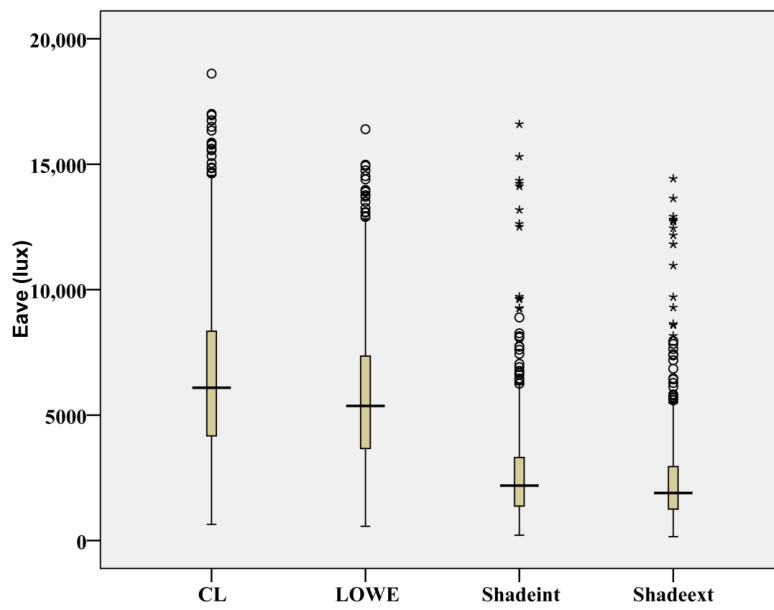
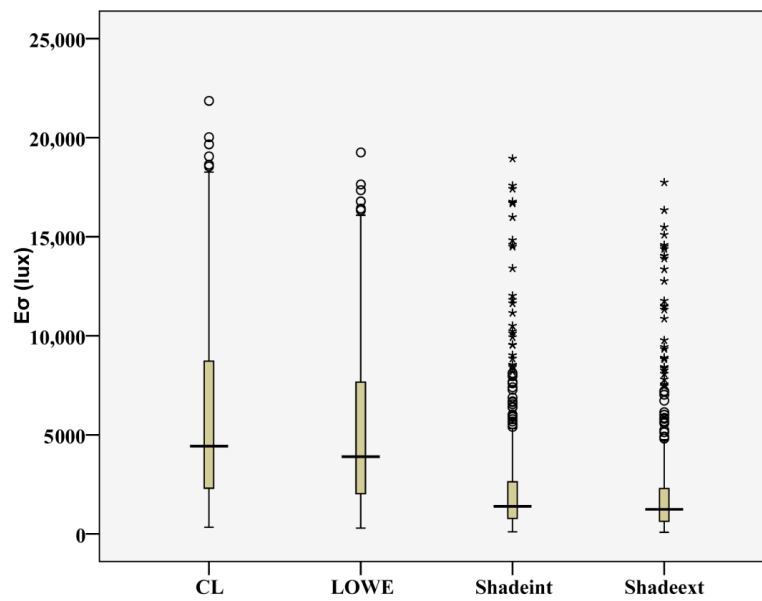**Figure 4.** Daily average daylight illuminance for the four scenarios.

Figure 5. Daily standard deviations of daylight illuminance for the four scenarios.

Table 5. Annual average of E_{ave} and E_σ for the four scenarios (lux).

	Cl	LOW-E	Shadeint	Shadeext
E_{ave}	6758.73	5955.12	2923.18	2670.75
E_σ	6088.04	5363.71	2631.08	2360.85

(**a**)

(**b**)
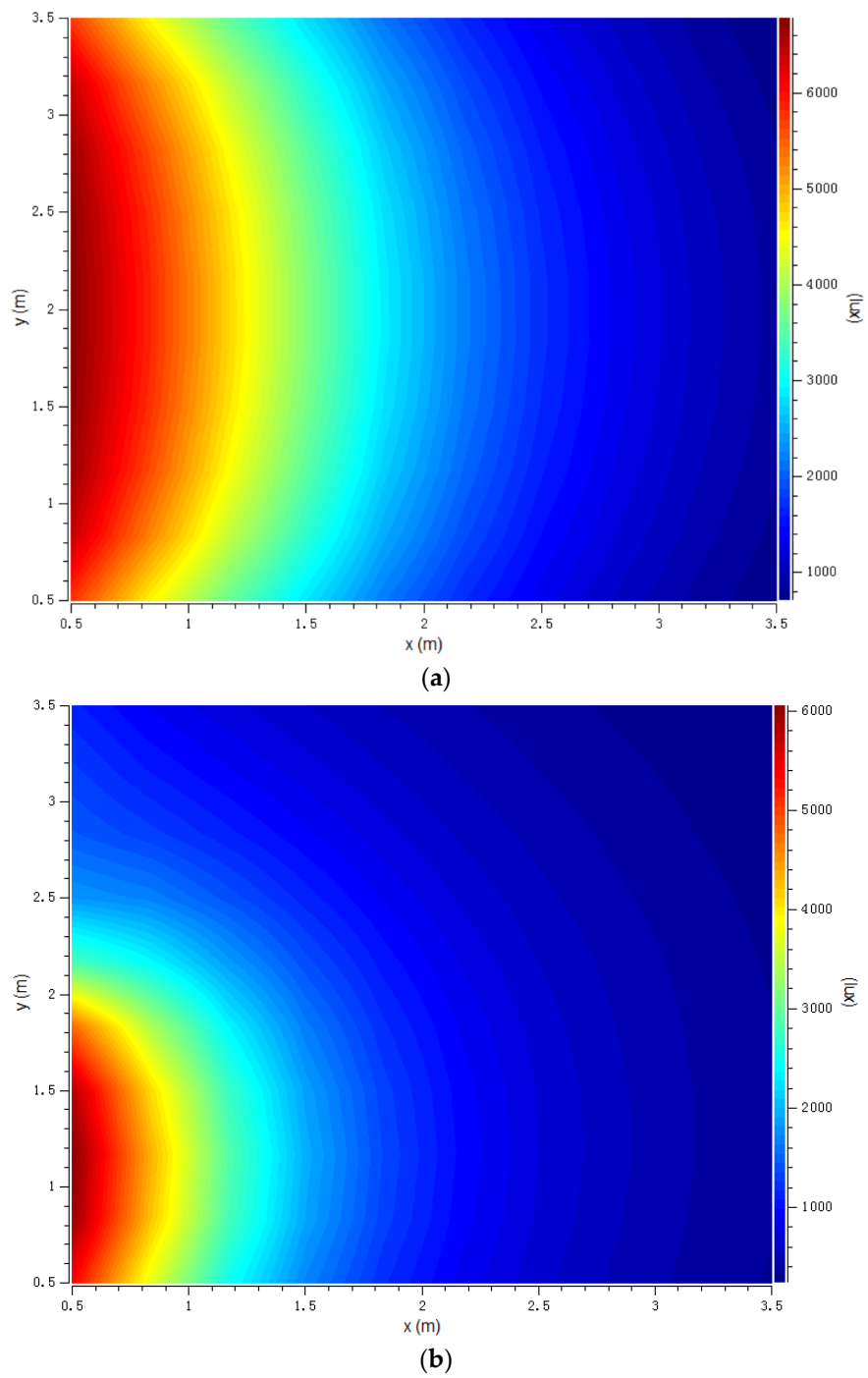
Figure 6. Daylight illuminance map of the office room at 15:00 on 28 June. (**a**) CL; (**b**) Shadeint.
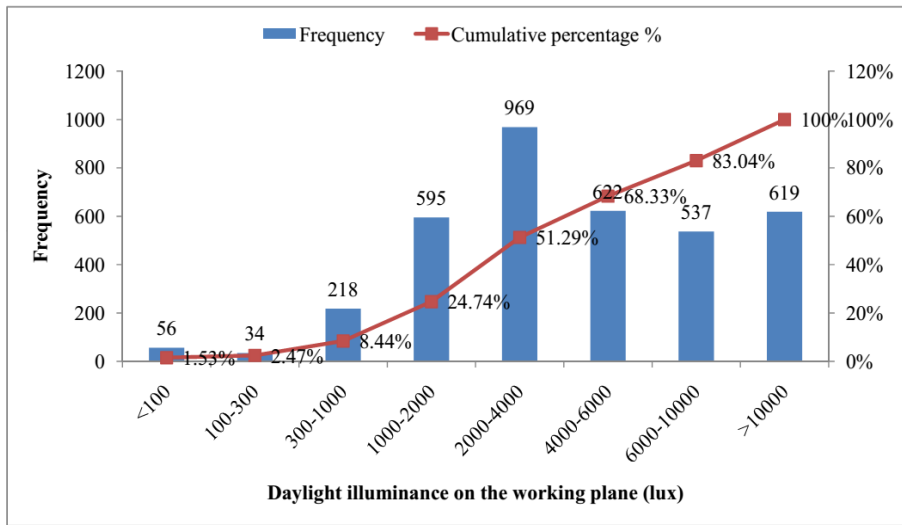
(**a**)
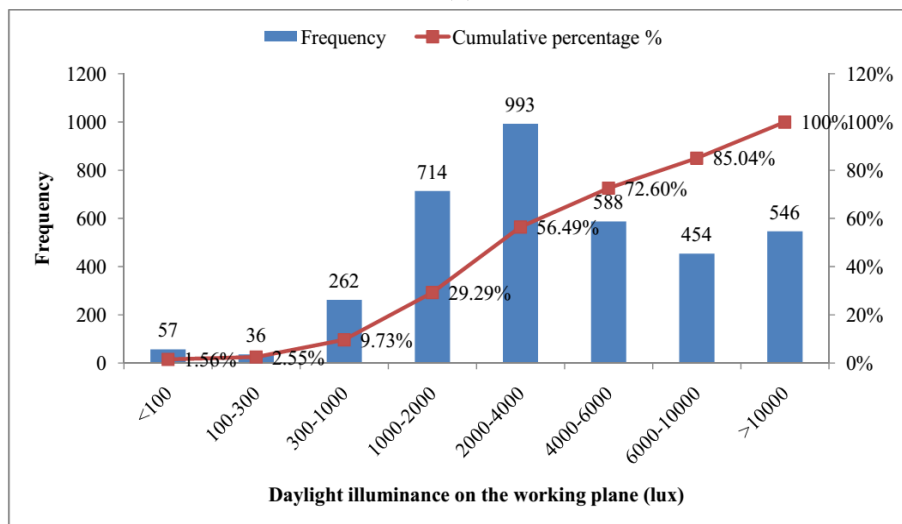
(**b**)
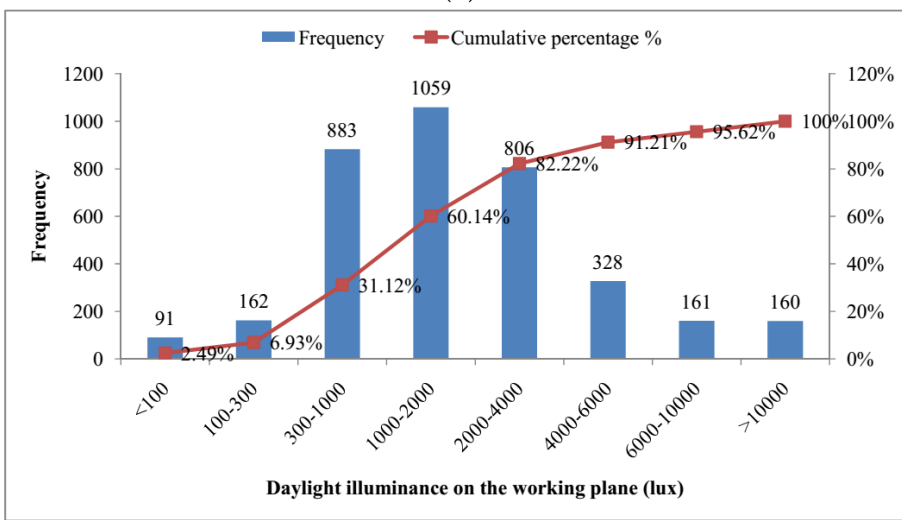
(**c**)

Figure 7. *Cont*.
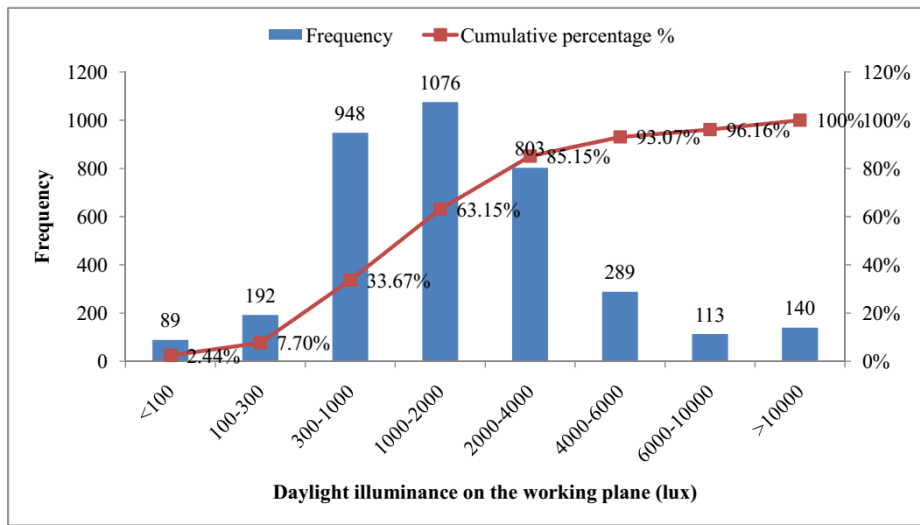
(**d**)

Figure 7. Distribution and cumulative percentage of daylight illuminance for the four scenarios. (**a**) Cl; (**b**) LOW-E; (**c**) Shadeint; (**d**) Shadeext.

3.3. Daylight Glare Index

Annual DGI distributions for the four scenarios are illustrated in Figure 8. It can be seen that daylight glare is more significant in the afternoon due to the influence of sunlight on occupants during that time, especially after 13:00 (an obvious increase in DGI) when beam sunlight could reach occupants' eyes. Besides, DGI in winter is higher than that in summer since solar altitude is relatively low in winter and thus more beam sunlight entering indoor environment.
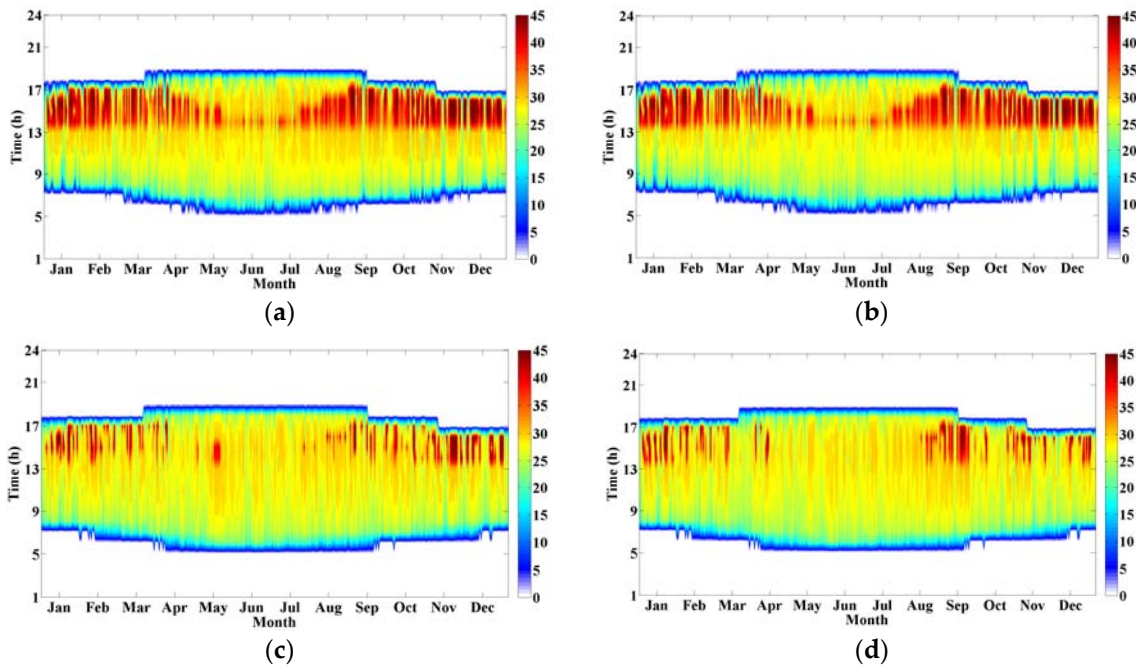

(**a**)

(**b**)

(**c**)

(**d**)

Figure 8. Annual Daylight Glare Index (DGI) distribution for the four scenarios. (**a**) Cl; (**b**) LOW-E; (**c**) Shadeint; (**d**) Shadeext.

DGI values for the four scenarios all reach a high value of approximately 45. However, Shadeint and Shadeext perform better than LOW-E and CL with less hours experiencing high DGI due to shaded window by solar shades. The average DGI is calculated in order to compare the four scenarios on the annual basis. The lowest average DGI is 27.79 for the scenario Shadeext, followed by Shadeint (28.03), LOW-E (28.58) and CL (29.29). Thus, movable solar shades also have a better glare protection.

3.4. Daylight Glare Probability

3.4.1. Glare Detection

The scenes for the four scenarios were simulated by Radiance and only part of the simulated scenes are illustrated in Figure 9 (with external movable solar shades at 16:00 on 1 July) as an example (similar scenes at other times or for other measures are also simulated but not presented here). The corresponding glare analysis is shown in Figure 10, where the blue circular zone at the center of computer screen is task zone and other colored zones are detected glare sources by Evalglare.
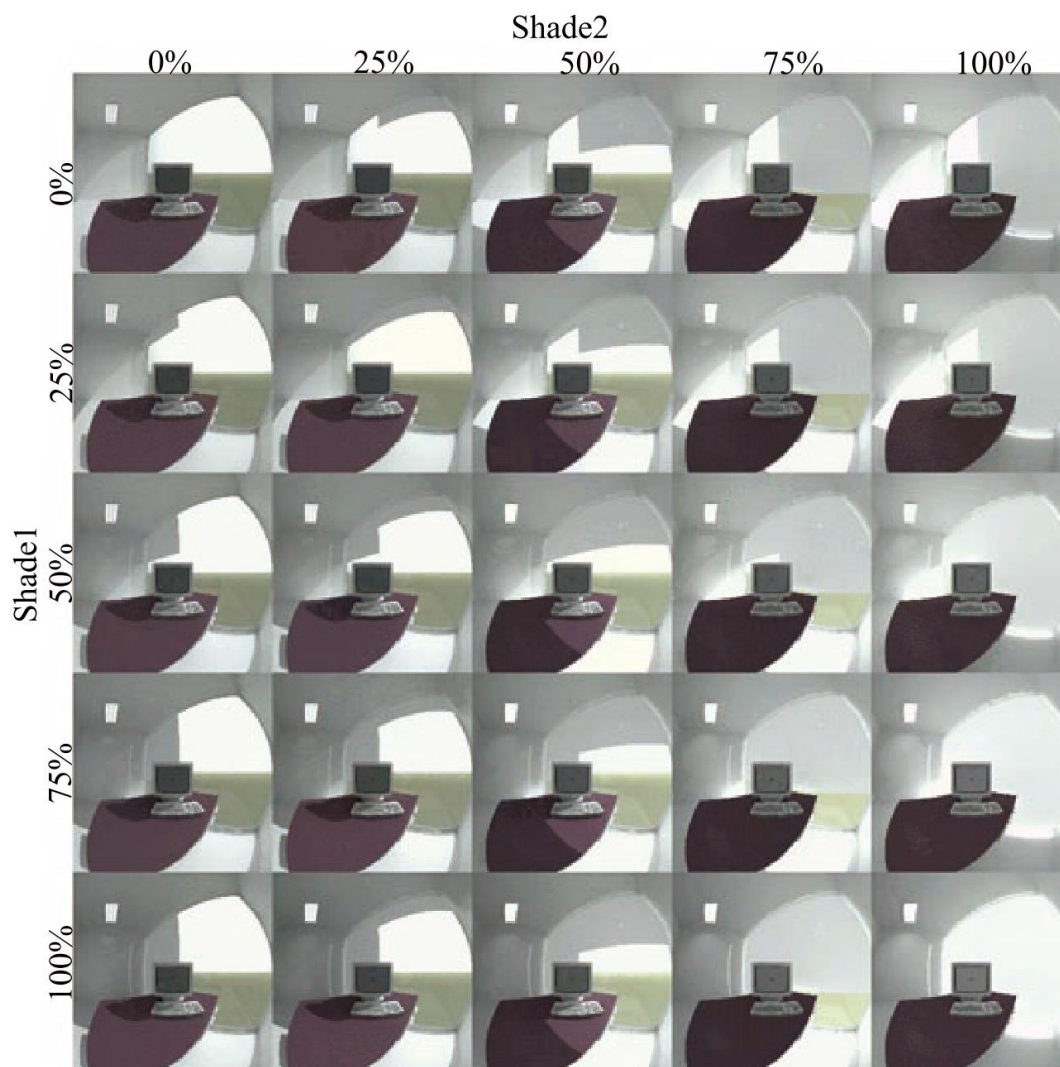

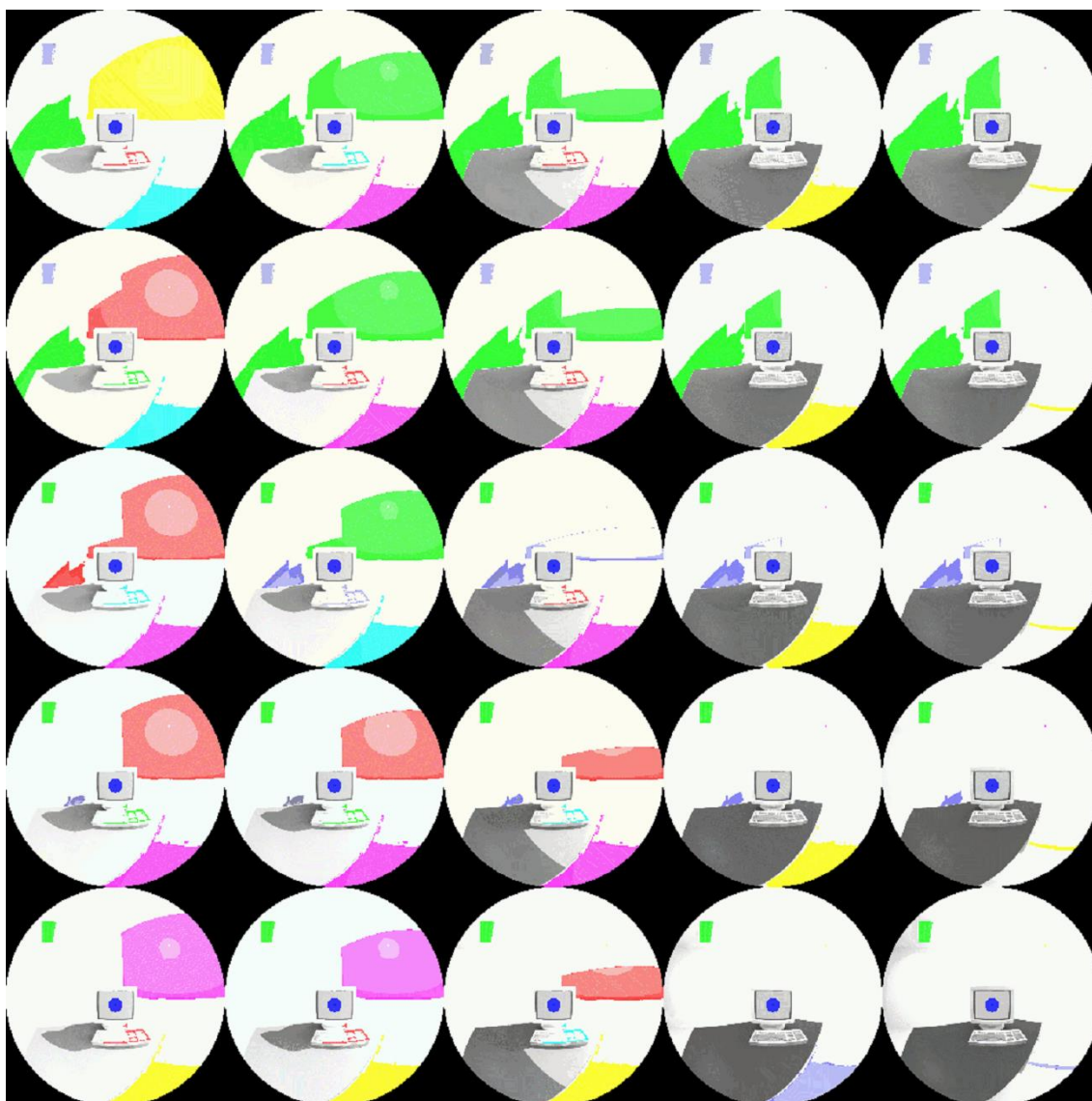**Figure 9.** Radiance simulated scenes for different movable solar shade positions at 16:00 on 1 July.

Figure 10. Detected glare sources for different external movable solar shade positions by Evalglare at 16:00 on 1 July.

3.4.2. DGP Scores at Different Shade Combinations

Meanwhile, Evalglare calculates and output DGP scores for these scenes. Due to a total of 25 scenes for Shadeext at a given time point of each season, DGP scores for these scenes are further illustrated using a colormap in the following Figures 11–13, where only scenes with DGP higher than 0.35 (glare is perceptible according to the above Table 3) are presented (Shadeint is similar to Shadeext and thus it is not illustrated here, it will be discussed in the following annual based analysis). It can be seen that glare is not significant at 14:00 while it will be intolerable for some shade positions during 15:00–17:00 in summer. However, DGP is generally less than 0.35 in summer if Shade2 is positioned to shade more than 50% of its window area, regardless of Shade1's position. This means that occupants could effectively avoid glare problems by deploying the Shade2 at a half position.

For the winter condition, both Shade1 and Shade2 have significant impact on DGP. Shade2 at a position of less than 50% shaded area leads to a DGP value of higher than 0.35 at 16:00, while Shade1 at a similar position results in a significant increase in DGP. In addition, DGP that is higher than 0.35 occurs from 13:00 to 16:00, the same number of hours as that in summer but one hour earlier. This difference compared to the summer situation is mainly due to the different sun positions in the sky (sun has relatively low altitude angles in winter condition).

For the transition season, DGP variation has a similar pattern at 14:00 to 17:00 to that in summer and the main difference is that DGP scores are higher for transition season, mainly due to relatively low solar altitude angles (more beam sunlight would enter indoor environment).The DGP variations in the three seasons all show that glare can be avoided or largely alleviated by deploying one side of the shade to about a 50% or 75% shading position. Thus, a balance among view toward outside, daylighting and glare protection would be achieved by partly shaded windows and this is generally the main control target of occupants' action on shades.
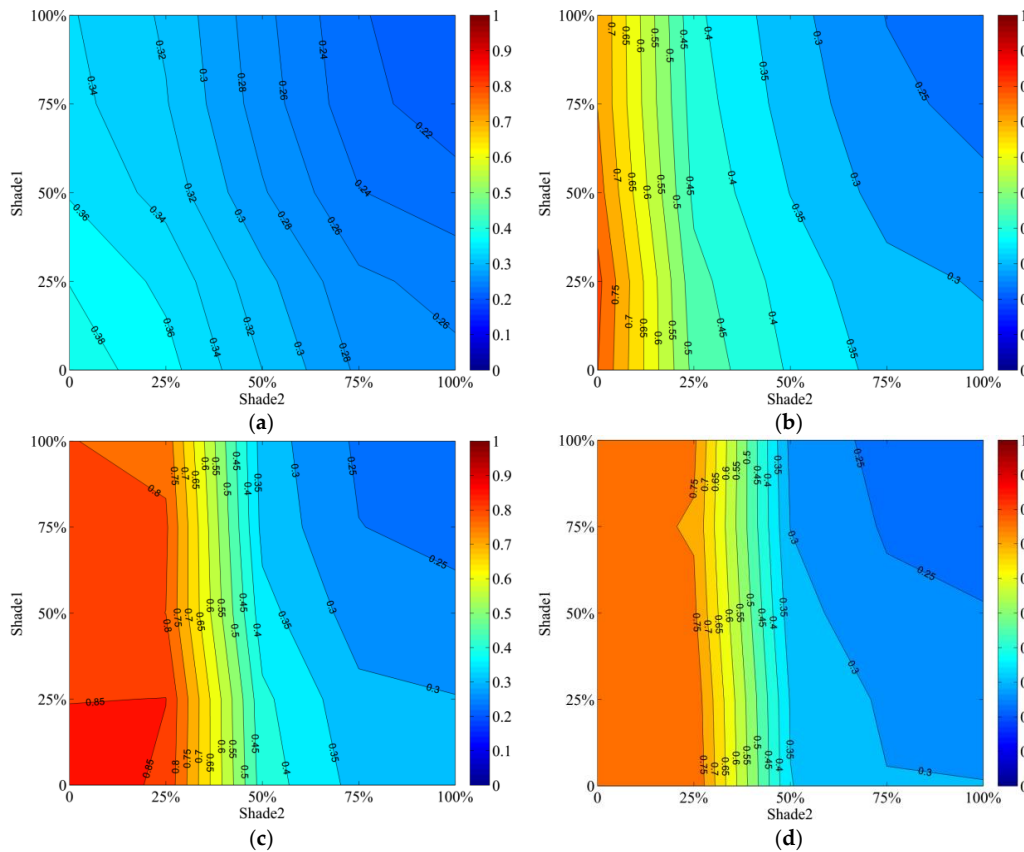

Figure 11. DGP scores at for different solar shades combinations during summer (only times with DGP > 0.35 is presented). (**a**) 14:00; (**b**) 15:00; (**c**) 16:00; (**d**) 17:00.
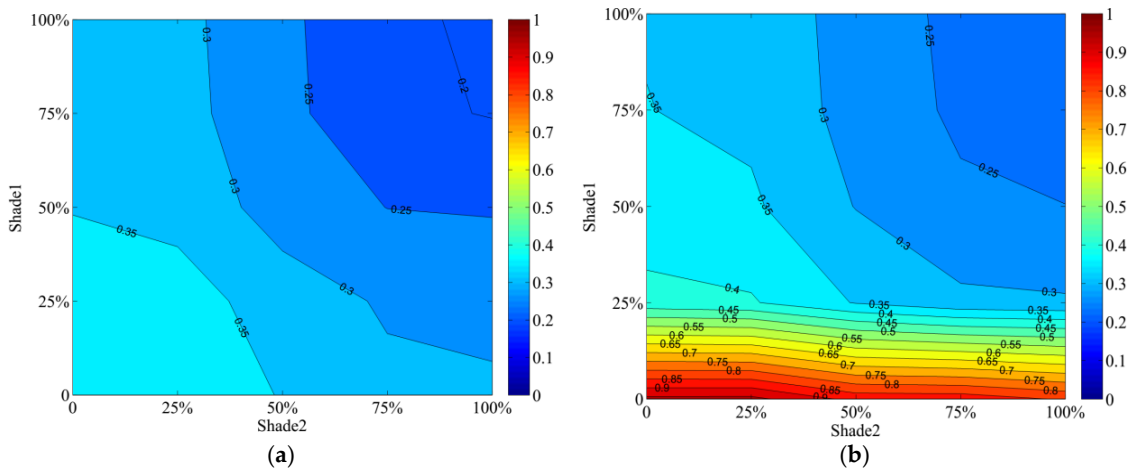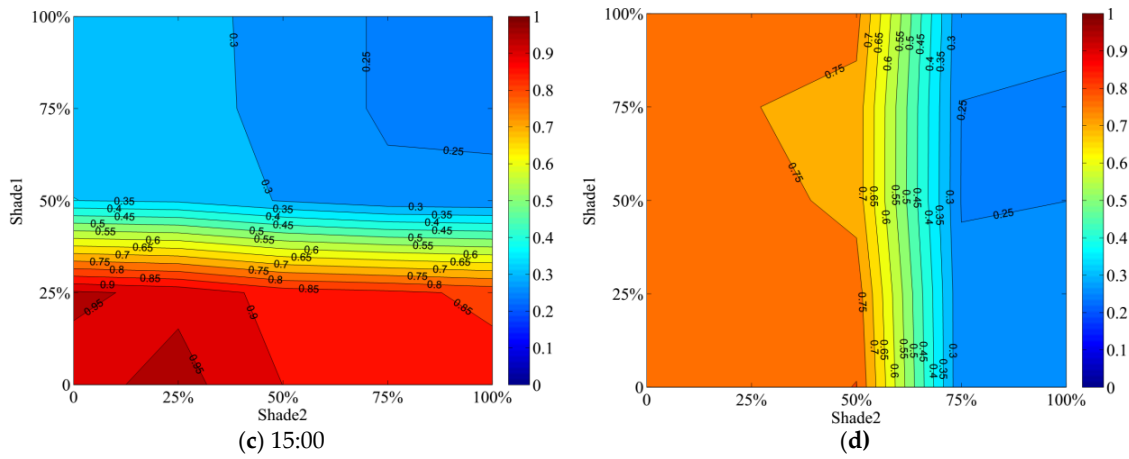

Figure 12. *Cont.*

(**c**) 15:00

(**d**)

Figure 12. DGP scores at for different solar shades combinations during winter (only times with DGP > 0.35 is presented). (**a**) 13:00; (**b**) 14:00; (**c**) 15:00; (**d**) 16:00.
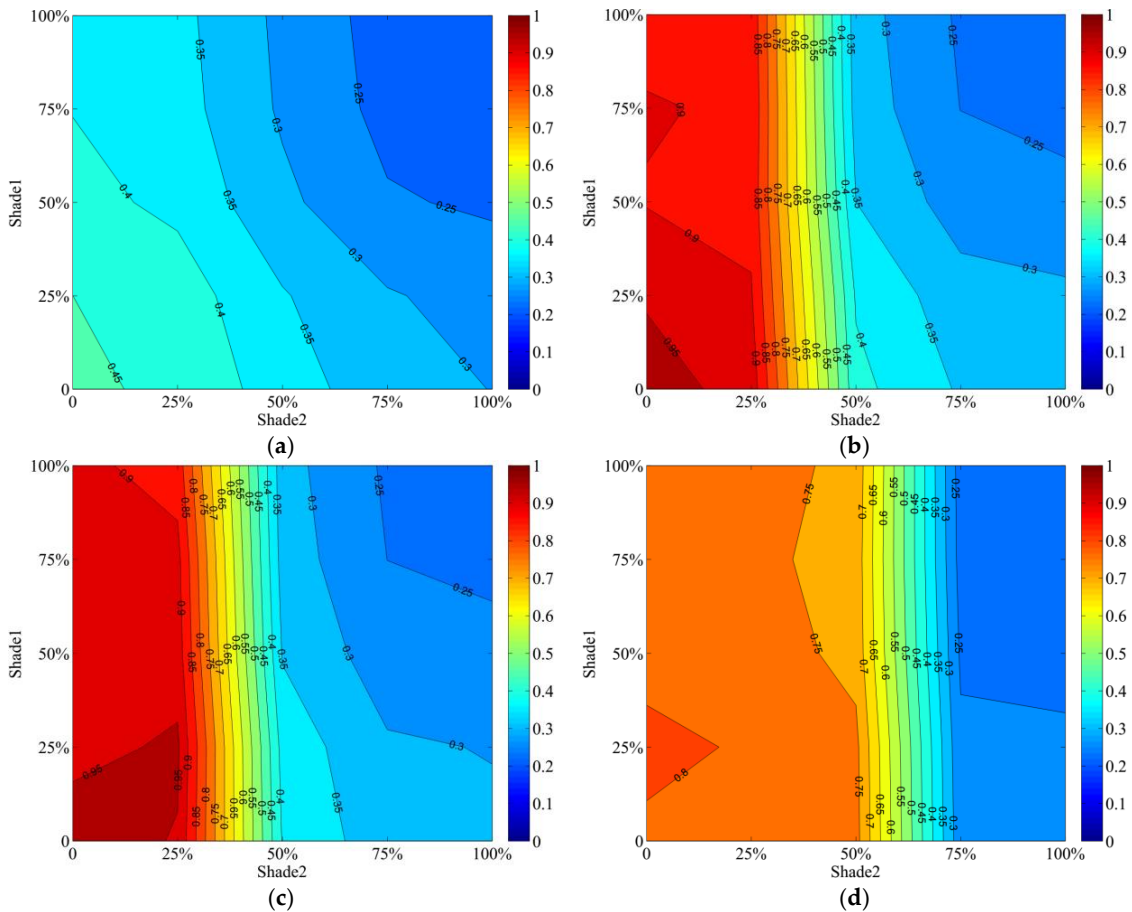

(**a**)

(**b**)

(**c**)

(**d**)

Figure 13. DGP scores at for different solar shades combinations during transition season (only times with DGP > 0.35 is presented). (**a**) 14:00; (**b**) 15:00; (**c**) 16:00; (**d**) 17:00.

3.4.3. Annual Glare Perception

The above analysis is based on all possible combinations of the positions of Shade1 and Shade2 and thus it cannot reflect the real occurrence of which combination is more frequent. Therefore, an annual based glare analysis is conducted. The combination of the position of the two shades at each

time point during each season is checked and then the glare perception according to the corresponding DGP score at each time point is counted. This way, the annual glare perception at each time point can be obtained.

Figure 14 shows the distribution of glare perception for the four scenarios annually during working hours (from 8:00 to 17:00). It can be seen that for more than 82% of time, glare is imperceptible for movable solar shades while this percentage is only 55.81% and 65.81% for CL and LOW-E, respectively. In addition, movable solar shades have a significant reduction (about 22%) in intolerable glare compared to CL and LOW-E. Therefore, movable solar shades have a significant improvement in glare protection compared with bare windows or low-e windows. Nevertheless, it can be seen that occupants' action on solar shades is not always effective in minimizing glare implication with about 12% of working hours experiencing intolerable glare. This may be attributed to occupants' delay on shade control [17] or other positive impacts such as a view toward outside, daylighting or the demand for sunlight in winter for warmth outweighs the negative effects of glare.

It also can be seen in Figure 14 that external solar shades also perform a little better than internal ones with a minor increase (3.17%) in DGP at the glare condition of imperceptible. Meanwhile, the extreme condition with intolerable glare is also improved (2.03%) when manual solar shades moved from internal side of windows to the external side. The main reason why the exterior shades perform a little better than the interior shades in terms of the above-mentioned indices is that the effectiveness of exterior shades in blocking unwanted direct sunlight in summer condition is higher than interior ones by 17.5% [17].
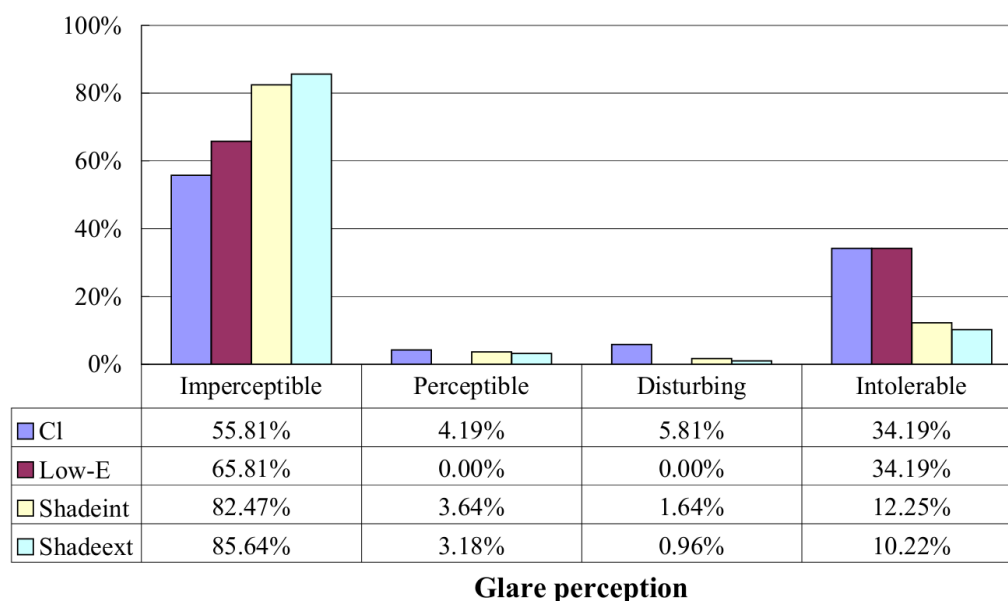

	Imperceptible	Perceptible	Disturbing	Intolerable
☐ Cl	55.81%	4.19%	5.81%	34.19%
☐ Low-E	65.81%	0.00%	0.00%	34.19%
☐ Shadeint	82.47%	3.64%	1.64%	12.25%
☐ Shadeext	85.64%	3.18%	0.96%	10.22%

Glare perception

Figure 14. Glare perception during annual working hours for the four scenarios.

4. Conclusions

The adjustment of manual solar shades relies on occupants' behavior, which is in fact stochastic. Thus, the impact of manual solar shades on indoor comfort is occupant dependent and the assumption of shades control with a fixed schedule cannot reflect the shade adjustment in reality. This paper tries to overcome this problem by taking into account the stochastic characteristic of occupants' shade control. A co-simulation study was carried out to evaluate the impact of manually controlled solar shades on indoor visual comfort. Several visual comfort indices, including useful daylight illuminance (UDI), daylight illuminance fluctuation (DIF), daylight glare index (DGI) and daylight glare probability (DGP), have been adopted to have a comprehensive comparison with normal low-e windows and clear pane windows.

The results showed that movable solar shades have more than half of the working hours with a comfortable illuminance level (useful daylight illuminance), which is about twice higher than clear pane windows and low-e windows. Meanwhile, the daylight illuminance fluctuation for movable solar shades is also significantly less. For glare protection, movable solar shades increase comfortable visual conditions (glare imperceptible) by about 30% compared to clear pane windows and by about 20% compared to low-e windows. Moreover, the intolerable glare perception can be reduced by more than 20%. When manual solar shades are adopted in building design, it is better to consider external solar shades rather than internal ones since external shades provide not only a better visual comfort condition as discussed above but also a comfortable indoor thermal environment [17] with less building energy consumption [13]. The findings of this paper can be applied to buildings with similar solar shades. For other shading types, however, the conclusion may be different.

Although the quantitative evaluation of the impact of manual solar shade control on indoor visual comfort has been provided based on a co-simulation analysis, further studies including long-term field measurements of occupants' visual perception will be needed to have a better understanding between occupants' stochastic shade control and visual perception and to give possible suggestions on improving shade control for a better indoor visual condition.

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