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Du, J, Zhang, X and King, D (2018) An investigation into the risk of night light pollution in a glazed office building: The effect of shading solutions. Building and Environment, 145. pp. 243-259. ISSN 0360-1323

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An Investigation into the Risk of Night Light Pollution in a Glazed Office Building: The Effect of Shading Solutions

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Abstract:

Light pollution has been recognised as a major environmental problem in urban areas at night. This study presents an investigation into the impact of seven various shading solutions on the risk of light pollution caused by indoor artificial lighting in a fully glazed office building. Radiance, a ray-tracing package, was adopted to calculate external illuminances produced by indoor lighting applications at various positions. It has been determined that: 1) A glazed façade could become a critical source of light pollution or obtrusive light (sky glow and light trespass) due to applications of indoor lighting at night; 2) A light shelf could perform well on the protection of both light trespass and sky glow; 3) A large overhang and horizontal louvre could effectively lower the risk of light trespass, but would possibly cause the deterioration of sky glow; and 4) No significant impact of short overhang and vertical louvre can be found on the two aspects of light pollution. This study exposes a significant implication; apart from their principal functions, the shading devices applied in a largely glazed building may require a new role in controlling obtrusive light in cities at night.

Keywords:

Light pollution, Shading solutions, Glazed façade, Indoor artificial lighting, Office buildings

1. Introduction

Light pollution, an environmental problem arising with the growth of urbanisation, can significantly affect sustainable developments in cities, especially in terms of ecological stability, human health and well-being, and energy conservation [1, 2]. Due to the broader use of artificial night lighting in urban areas, significantly increased ‘ecological light pollution’ has occurred, with negative effects on terrestrial and aquatic ecosystems [3, 4]. For example, it has been proven that excessive artificial lighting applications are the main reason behind the deaths of migratory birds and the disorientation of hatching sea turtles [3]. In addition, one study exposed that improper use of outdoor artificial lightings can disturb a human’s normal circadian rhythm [5]. The rapid growth rate of cancer has been linked with the increased light exposure in developed countries during the last 100 years [6]. As for energy conservation, uncontrolled outdoor artificial lighting systems (unshielded, over-lighting) account for a huge amount of wasted energy in urban areas at night [7].

Light pollution can be divided into three categories: sky glow, light trespass, and glare [8, 9]. The increase in the luminance of the night sky (produced by excessive artificial lighting) gives rise to sky glow, which is a combined effect of reflected and refracted light from the atmosphere [10]. Sky glow can have a negative impact on the environment across a large-scale urban area or region. However, as a local light pollution phenomenon, light trespass occurs when an unwanted spill of exterior light enters into a building and illuminates an indoor space [8]. This type of obtrusive light is typically brought by light installations beyond the property boundary. Based on a large luminance contrast between the light source and the darker background, outdoor lighting can cause both discomfort and disability glare [8]. Compared with sky glow and light trespass, it could be more difficult to measure and control the glare in urban areas at night, since it is relevant to the physiological and psychological functioning of human beings. Regarding installations and types of outdoor lighting, light pollution is linked with street lighting, façade lighting, sign/advertisement lighting, and security lighting, etc [11, 12].

Environmental zoning systems are a qualitative approach that have been used to control and manage exterior lighting installations and limit obtrusive lighting in various urban/rural areas. In 2003, the Commission Internationale de l’Eclairage (CIE) preliminarily defined a four-zone system based on the ‘night brightness’ of the local environment as follows [13]: ‘E1: Areas with intrinsically dark landscapes: national parks, areas of outstanding natural beauty (where roads are usually unlit); E2: Areas of low-district brightness: outer urban and rural residential areas (where roads are lit to residential road standards); E3: Areas of middle-district brightness: generally urban residential areas (where roads are lit to traffic route standards); E4: Areas of high-district

brightness: generally urban areas with mixed recreational and commercial land use with high night-time activity.’ For each environmental zone, the maximum values of light technical parameters (quantitative standards) were recommended according to vertical illuminance on properties, intensity and upward light ratios of luminaires, glare, surface luminance of building façade, and signs. Clearly, E1 has the strictest standards for setting lighting systems, while a relatively larger range of lighting installations can be applied in E4. It can be also noted that the limitations of lighting values in each zone have clear differences between pre-curfew and post-curfew time. Based on collaboration of the Illuminating Engineering Society of North America (IESNA) and the International Dark-sky Association (IDA), a model lighting ordinance (MLO) proposed a new system with five lighting zones (LZ: 0-4) [14]. Lighting Zone 1–4 corresponds to the CIE system respectively, while Lighting Zone 0 is only applied in ‘intrinsically dark’ areas, in which no permanent lighting should be installed or expected. Such areas include protected wildlife zones and corridors, IDA Dark-sky Parks and major optical observatories [14]. Later, the Institute of Lighting Professionals (ILP) and the Society of Light and Lighting (SLL) adopted all five environment/lighting zones in their recommendations to manage lighting design and installations [15, 16], especially in cities. The recent updates in the previous CIE guide (CIE 150-2003) on obtrusive light [13] have led to a new guide [17], which includes Lighting Zone 0 and relevant lighting limitations.

Given the typical lighting installations in urban areas, a number of research activities have been conducted with an aim to control and/or assess light pollution. Since 2005, several codes have been developed to limit light pollution from exterior lighting fixtures. BUG (Backlight, Uplight, and Glare) ratings were proposed by the IESNA as a metric for evaluating luminaire’s 3D photometric distribution of impact on light trespass, sky glow, and glare [18, 19]. The CIE adopted a similar system of ULO (Upward Light Ratio) for exterior luminaires, focusing on limiting the sky glow [17]. Both BUG and ULO metrics did not directly include the reflected upward components of specific lighting installations. Thus, UFR (Upward Flux Ratio) [17] was recently introduced by the CIE, considering the luminous flux reflected from the intentionally lit surface area and the surrounding surface area lit by the spill light. Some research investigations have tried to include more urban environmental factors, such as buildings, transportation systems, and landscapes. An earlier study in a Latin American city produced a methodology to model urban light pollution through the integration of relevant surfaces, such as roads, pedestrian pathways, building façades, and the spectral/diffuse reflection of the main vegetation [20]. This study quantified the main performances of these urban environmental factors, regarding the contributions to sky glow, and, therefore could be adapted to support a broader range of exterior lighting design. Similarly, the Light Pollution Index (LPI) [21] was another approach to justify the combined effect of direct and reflected upward flux from

street and façade lighting. In cities, sign/advertisement lighting has also been recognised as a typical light pollution source, especially in Eastern Asia [22, 23]. Such signs have three distinct forms, including internally illuminated signs, externally illuminated signs, and self-luminous signs [16]. To limit these obtrusive lights, the CIE has recommended the average surface luminance limitations of signs in different environmental zones [13], whilst both the size and surface luminance of signs have been included into a similar standard of SLL [16]. However, these limitations might not be as effective in dense urban areas. A study in South Korea [22] has exposed that the CIE luminance limitations of signs cannot practically reduce the risk of light trespass on the windows of residential buildings in a dense urban area. In addition, the luminance recommendations [13, 16] might not be suitable for a large/continuous façade area with signs. Another investigation found serious light trespass would still occur even though the surface luminance of a larger sign façade was set as lower than CIE limitations [23]. Apart from sky glow and light trespass, glare (discomfort and disability) from outdoor lighting installations is more difficult to measure and predict due to its psychophysical characteristics [16]. Based on a series of experiments, a simple model was proposed to predict discomfort of outdoor glare by linking ambient and light source illuminance values with the De Boer glare scale [25, 26]. Moreover, a recent study [27] investigated the indoor visual discomfort brought by the light trespass of outdoor lighting installations in a highly dense city. These studies again emphasise the complexities of glare evaluation and predictions. Regarding a general method to predict and measure three different aspects of light pollution, only one framework, ‘Outdoor Site-Lighting Performance’ (OSP) was produced, based on the survey of a broader range of outdoor lighting installations in the USA [28]. OSP uses a hypothetical calculation ‘box’ surrounding an outdoor lighting installation to predict the level of light leaving the site and therefore providing a quantitative technique to help lighting specifiers design outdoor lighting systems with the lowest risk of light pollution [28].

More importantly, there is always a conflict concerning outdoor lighting application in cities, i.e. the need for such lighting and the need to reduce light pollution [2, 8]. As emphasised in a code [8], outdoor lighting can valuably contribute to people’s work, safety, and enjoyment after dark, but it can also bring in light pollution, such as sky glow, light trespass, or glare. If the design and use of urban outdoor lighting can be carried out using a proper approach [7–8, 11–13], such a conflict would be avoidable.

Currently, a high-speed growth of urban areas can be found in Eastern Asia, in particular, China [29]. A large number of dense areas with commercial, public, and residential buildings have been increasingly developed in cities. In Beijing, the capital of China, most newly built commercial buildings have adopted a modern ‘hi-tech’

architectural style, i.e. structural expressionism and façades with largely glazed areas. At night, such façades become a light source due to the spill light from the indoor lighting applications (several examples can be found in Figure 1). This ‘overnight lighting’ can be found for several possible reasons: (1) security and crime prevention [30] – both internal and external lights will have to be kept on; (2) people working at night (e.g. staff working late, multiple shifts, and cleaning work); (3) city nightscape requirements – building façades will be lit up to present a proper appearance. As a result, this ‘shining façade’ at night can significantly increase the risk of light pollution based on sky glow, light trespass, and glare. A famous case was recently reported in the online lighting publication, Lux Review [31]: the night light burning across all three floors of a store in Hong Kong spilled out of the glass façade, bringing in serious light nuisance and complaints. However, no substantial research investigations have been implemented based on such light pollution phenomenon. In the daytime, a building with a largely glazed façade will necessarily use shading devices to reduce indoor glare and overheating problems [32, 33, 34]. Compared with the bare window, the shading devices can possibly block or help deliver light from both sides of the façade. A research question is being raised according to the discussions above: how does the installed façade, with various shading solutions, impact on the light emitting from the indoor environment at night?



Figure 1. Examples of ‘shining façade’ of glazed commercial buildings in cities (with the internal lighting on).

Thus, this article presents a simulation study with an aim to examine the external illuminances caused by the indoor lighting in a fully glazed multi-storey office building in Beijing at night. Various shading solutions were considered and their impact on the risk of light pollution (only for upward light and light trespass) were assessed.

2. Methods and materials

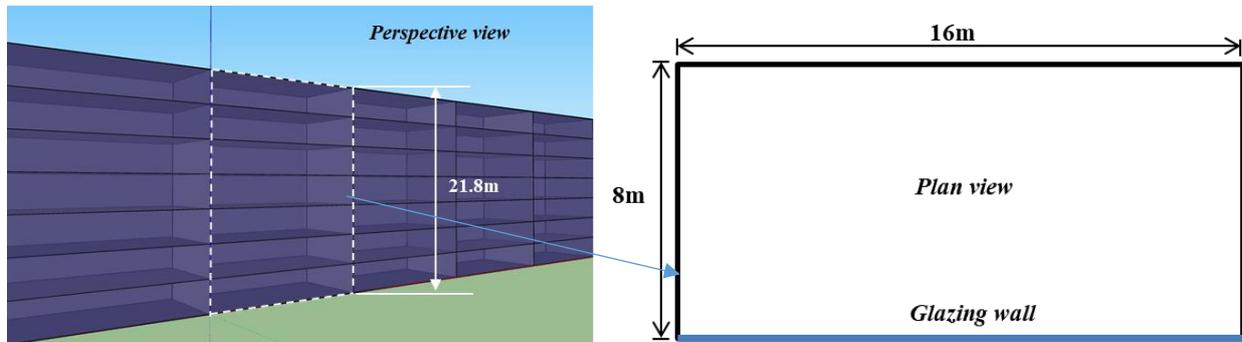
2.1 Building and shading devices

A typical seven-storey office building was studied in Beijing, with a fully glazed front façade (Figure 2 [a]). Architectural configurations of the building were defined using regulations [35, 36]. The entire height of the building was 21.8m, whilst its length was set as a value far larger than the height. As discussed in a preliminary study [37], the large length was chosen to produce an ‘infinite’ horizontal dimension, because varying vertical configurations of façades were the research focus. Thus, only the middle unit (marked by the white dash) was analysed as the representation. Each floor of the middle unit had the same open-plan office room (Figure 2 [a]), with the dimensions 8m (depth)×16m (length)×3m (height). The dimensions were chosen based on considerations such as: 1) to produce a normal large open-plan workspace in the building [38]; and 2) to lower the influence of internal walls and therefore focus on the impact of the façade (glazing and shading devices) on emitting light outwards. The setting of the same room on each floor was used to check the combined effects of room and shading devices at various heights on external lighting levels (for justifying light pollution risk) (see Section 3).

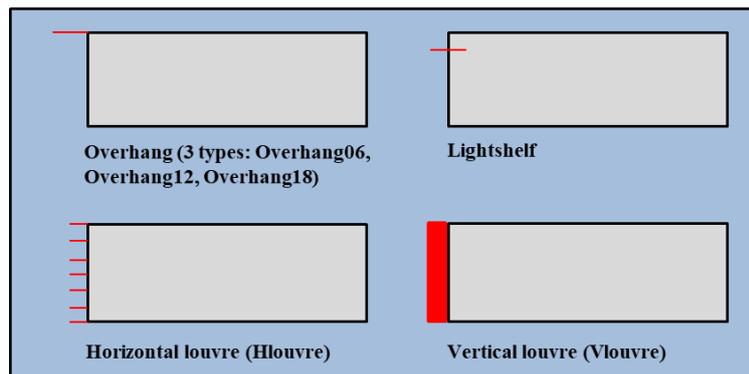
Internal surfaces and façade configurations of this office room were decided using recommendations of lighting codes [39, 40]. The internal surface reflectances of this room were 0.6 (wall), 0.8 (ceiling), and 0.3 (floor). With a double-glazing system suggested by the code [35, 39], the fully glazed façade can provide the room with a ratio of window area/floor area > 20% (the minimum requirement [39]). The choice of such façade was based on the aim to check the ‘worst’ situation relating to light pollution brought by indoor lighting [37]. The façade was then modelled based on a typical double-glazing system from the International Glazing Database [41], including 3.9mm low-E glass (external), 12mm air gap (middle), and 3mm clear glass (internal). The overall visual transmittance of the glazing was 0.745. Surface reflectance of the external ground was set as 0.2.

In this article, four common types of fixed shading device were studied, including overhang, light shelf, horizontal louvres, and vertical louvres (Figure 2 [b]) [42, 43, 44]. The overhang is for solar shading and can therefore retain a proper thermal comfort by reducing excessive solar heat gain to the interior [42, 43]. This type of overhang can be defined in terms of depth, i.e. small, medium and large [42], which relates to the obstruction of the sky. Apparently, a greater depth will block more incidence of solar radiation or daylight, especially from a higher altitude. As comprehensively discussed in the study [44], light shelf can be either exterior, interior, or both. An external shelf has the main function of shading internal areas next to the window, while an internal shelf provides visual protection from sun glare at the intermediate depths within a room [44]. Used for solar protection, the fixed

horizontal and vertical louvres are applied at locations dominated by clear sky [42, 43]. Horizontal louvre is generally placed at south, east, and west façades at the northern hemisphere. The best orientation for setting vertical louvre is east or west, since it can effectively block excessive sunlight coming from the side. It has been determined that facing the same orientation, the vertical louvre will block less higher-altitude sky than the horizontal louvre [42].



a) Perspective view of building model (the middle unit marked by the white dash line) and the same office room was set at each floor.



b) Four types of shading device (room sections). The same shading device was set at each floor.

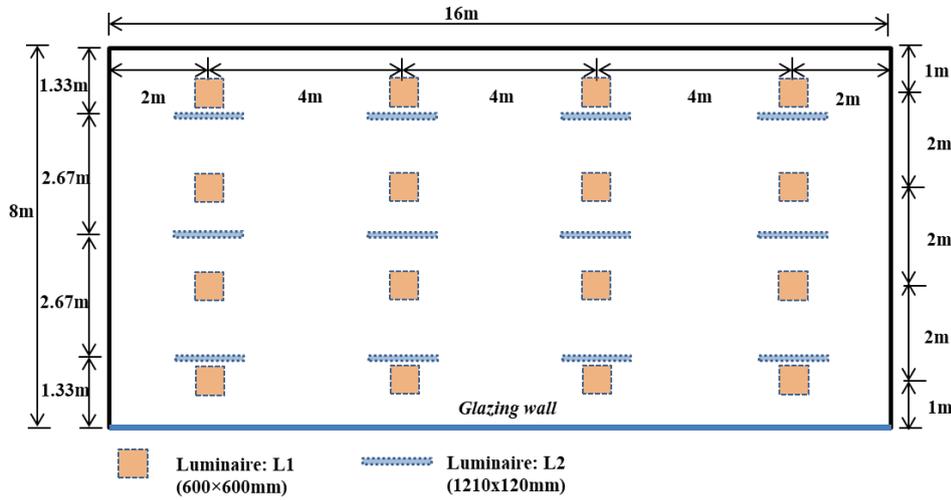
Figure 2. Building model and room plan (a); and shading devices studied in this article (b).

In this article, three types of overhang were studied as follows: Overhang06 (small depth 600mm), Overhang12 (medium depth 1200mm) and Overhang18 (large depth 1800mm), which were chosen based on a balance of solar shading and daylight availability [42, 43]. Following design guidelines [44], the light shelf (Lightshelf) in this article was installed at a distance of 500mm from the room ceiling and had internal and external components with a depth of 600mm [44]. In addition, configurations of vertical and horizontal louvres in this article could achieve a balance of blocking solar gain and obtaining daylight [42]. With a short depth of 300mm, the horizontal louvre (Hlouvre) was evenly distributed from bottom to top façade on each floor. The distance between the adjacent louvres was set as 500mm. To compare with the horizontal louvre, the vertical louvre (Vlouvre) had a depth of 300mm and the same distance of 500mm between two adjacent vertical fins. As suggested in several studies [42, 43, 44], the six shading devices used a white matt material (reflectance: 0.8).

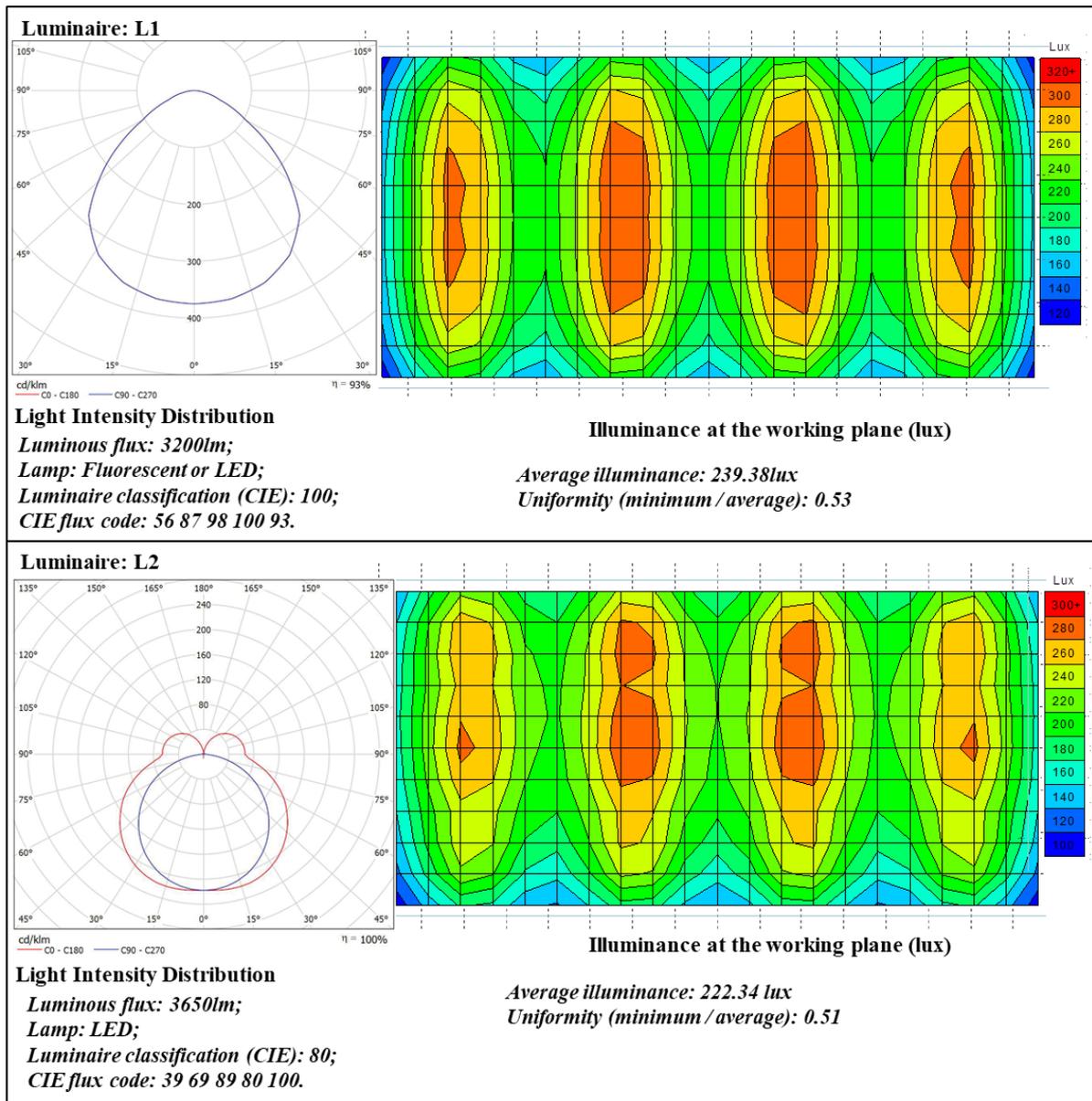
2.2 Indoor artificial lighting systems

In this article, a general lighting application in each office room of the building was considered at night. This lighting system was designed taking into consideration two aspects: 1) the requirements of security and urban nightscape in Beijing or other cities [45, 46], which need to keep the internal lighting on at night; and 2) energy efficiency relating to landscape lighting applications [45]. The lighting system will provide a medium illuminance ranging from 200 to 250lux at the working plane (0.8m above room floor). The range was defined based on an assumption: the night illuminance can be set at around half of the standard used in normal working time (i.e. 500lux [40]), to balance night lighting needs and save energy in the building.

According to Figure 3, two ceiling-mounted luminaires of L1 and L2 were applied separately in the room. They were typical office luminaires found in the current Chinese lighting market. The L1 has a common square plan (600×600mm) and a simple light intensity distribution (lighting type: direct [40]; luminous flux: 3200lm), whilst the L2 was a linear luminaire (1210×120mm; lighting type: direct and indirect [40]; luminous flux: 3650lm) with different intensity distributions at the planes of C0-C180 and C90-C270. For L1, the distribution of light intensity (C0-C180 = C90-C270) shows that this luminaire can emit the light flux rotationally symmetric. The flux code (56, 87, 98, 100, 93) also exposes that over 50% of its total light flux can be delivered downward in a small solid angle of $\pi/2$. However, for L2, the flux code (39 69 89 80 100) gives rise to a different flux distribution as: 1) 80% of the total flux is going downward; 2) 20% of the total flux is going upward; and 3) only 39% of the total downward light flux is within the solid angle of $\pi/2$. Also, it can be found from the distribution curve of L2 (Figure 3) that the upward flux occurs along the width of luminaire (C90-C270; the direction perpendicular to façade). In comparison to L1, L2 can send more light towards the window than L1. Based on optimised design solutions using a professional lighting software of DIALUX [47], 16 and 12 fixtures were required to achieve a proper illuminance level at night for L1 and L2, respectively (Figure 3 [a]). The two solutions led to the average illuminances of 239.38lux (L1) and 222.34lux (L2) on the working plane (Figure 3 [b]). Both solutions had the illuminance uniformity > 0.5 across the room.



a) Two types of indoor lighting systems for night application (L1 and L2).



b) Photometric properties of two luminaires (L1 and L2) and their lighting performances at the working plan.

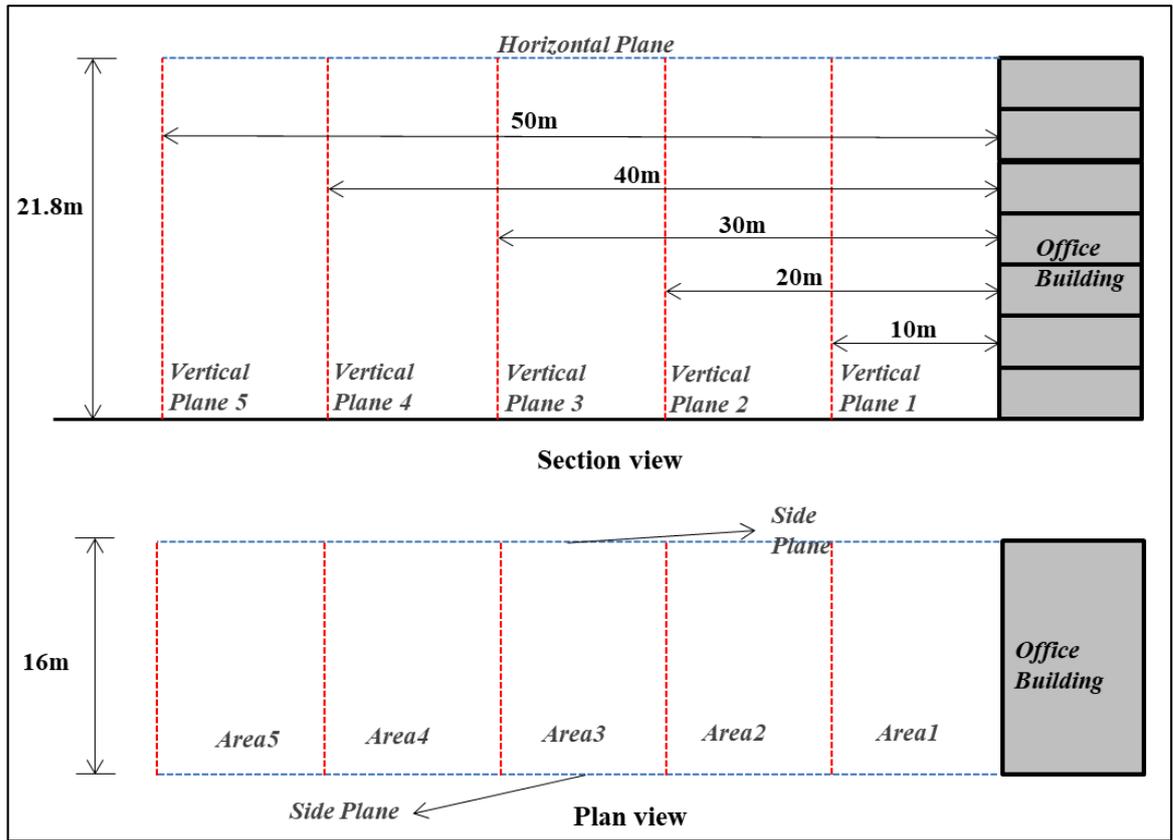
Figure 3. The night lighting applications and the photometric properties of two various lighting systems (L1 and L2) in each open-plan office.

2.3 Simulations of external illuminance levels

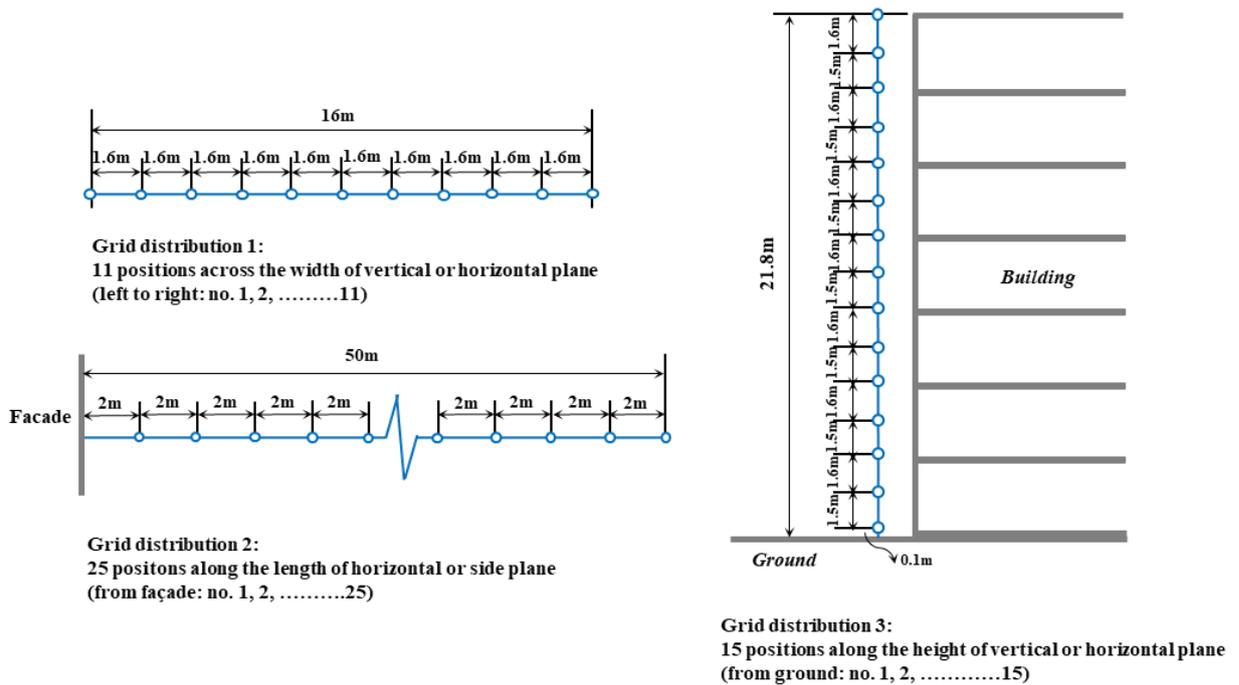
To quantify the light released from the glazed façade of the office building at night, vertical, horizontal, and side calculation planes were set up on the external side of the façade (Figure 4 [a]). These planes were built up using the same approach as the ‘virtue box’ suggested in the OSP method [28]. The original ‘virtue box’ used a virtual and transparent box to cover a property in a city. It had vertical sides at the property boundary and a flat ‘ceiling’ placed above the highest point of the property illuminated by artificial lighting at night. However, in this study, the ‘virtue box’ has been modified as a new one, with only three vertical sides and one ceiling. It was used to cover the façade surface and then measure the emitting light from the interior. In line with the façade dimension (21.8×16 m), the vertical plane paralleling with the façade (VP) had five types. The types were defined in terms of distance from the façade as follows: 10m (VP1), 20m (VP2), 30m (VP3), 40m (VP4), and 50m (VP5) (Figure 4 [a]). The setting of the five VP aimed to measure the decay of light with an increasing distance from the façade. In cities, this could be used to justify the risk of light trespass (e.g. obtrusive light received at the windows of adjacent buildings) [16]. The distance of 50m could be a position that can receive a very low lighting level based on this study. Second, one horizontal plane was placed across the five vertical planes and at the same level as the building top (width × length: 16 × 50m). Therefore, two side planes were adopted to cover the side of this ‘virtue box’ in front of the glazed façade (width × height: 50×21.8m). Three various calculation grids were applied at the three different planes (Figure 4 [b]). Each vertical plane had a calculation grid with 11 positions across the width (Grid distribution 1; the distance between the two grids is 1.6m) and 15 positions along the height (Grid distribution 3). Vertically, the heights of the 15 positions above ground were 0.1m, 1.6m, 3.2m, 4.7m, 6.3m, 7.8m, 9.4m, 10.9m, 12.5m, 14m, 15.6m, 17.1m, 18.7m, 20.2m, and 21.8m. However, for the horizontal plane, 25 positions were evenly distributed along the length (see Grid distribution 2; the distance between two positions was 2m), whilst the grid distribution (1) was applied across the width. Furthermore, the side plane had a grid of 25 and 15 positions along the length (Grid distribution 2) and the height (Grid distribution 3) respectively. The position number of each grid distribution was also given. Vertical planes and the façade divided both the horizontal and side planes into five areas (Area 1–5) (Figure 4 [a]).

As emphasised in the OSP [28], a comprehensive analysis of the light leaving one site will have to rely on a simulation tool capable of calculating interrelations of light. To effectively simulate light reflection and transmittance occurring in both internal and external spaces, a ray-tracing package will be required. Radiance [48], a backward ray-tracing package, was adopted as the main simulation engine to calculate the external illuminances at specific positions of each external plane. Validated over 10 years, Radiance was commonly used

to investigate daylighting performances in buildings with complicated fenestration systems (e.g. overhang and light shelf) and under various sky conditions [48]. However, it is also practical to apply Radiance in spaces with only artificial lighting systems [48]. To simulate artificial lighting, this study has used a sub-programme 'IES2RAD' of Radiance to convert the IES files of luminaires used in the office building into Radiance scene descriptions. Then, Radiance can calculate illuminances at any position in the scene. Radiance description of the façade glazing was produced from the International Glazing Database (version 40.0) [41] and Optics6 [49]. When calculating illuminances at various planes, the normal direction always faced the internal side as: facing the façade (vertical planes), downward (horizontal plane), and inward (side plane).



a) Positions and dimensions of Vertical, horizontal and side planes.



b) Grid distributions at vertical, horizontal and side planes.

Figure 4. Vertical, horizontal and side planes and calculation grids for the external illuminance calculations (section and plan views).

3. Results

This section presents variations of external illuminance across vertical, horizontal and side planes, with seven shading solutions (unshaded and using shading devices) and two indoor lighting systems (luminaires: L1 and L2). The ‘Barewindow’ stands for the model with an unshaded façade.

3.1 Illuminance variations on vertical planes

In order to analyse the differences in illuminance at various heights of five vertical planes (VP) between shaded and unshaded models, a value R_{ve} was introduced as follows:

$$R_{ve}(j) = \frac{E_{av,bw}(j) - E_{av,sh}(j)}{E_{av,bw}(j)} \times 100\% \quad (1)$$

$$E_{av,bw}(j) = \frac{\sum_{i=1}^{11} VE_{bw}(i,j)}{11} \quad (2)$$

$$E_{av,sh}(j) = \frac{\sum_{i=1}^{11} VE_{sh}(i,j)}{11} \quad (3),$$

where, $R_{ve}(j)$ is the relative difference of average vertical illuminance at the vertical position (j) between models with Barewindow and shading devices (unitless);

$E_{av,bw}(j)$ and $E_{av,sh}(j)$ are the average vertical illuminance of 11 horizontal positions (i) at the vertical position (j) for the model with Barewindow and shading devices respectively (lux);

$VE_{bw}(i, j)$ and $VE_{sh}(i, j)$ are the vertical illuminance at the position (i, j) for the model with Barewindow and shading devices respectively (lux);

i, j is the position at the vertical plane with Grid Distribution 1 and 3 respectively (Figure 4 (b)), i= 1, 2,11, j= 1, 2,15.

Second, average vertical illuminance (AVE) of all grids across each vertical plane was calculated by the following equation:

$$AVE = \frac{VE(i,j)}{11 \times 15} \quad (4),$$

where, VE (i, j) is the vertical illuminance at the position (i, j) of one vertical plane.

3.1.1 Variations in vertical illuminances along the height of plane

Figure 5 demonstrates variations of average vertical illuminance of Barewindow ($E_{av,bw}$) at 15 heights of five vertical planes with L1 and L2. Apparently, $E_{av,bw}$ varies in terms of distances from building façades and heights above ground, whereas the impact of height tends to be lower with an increasing distance from the façade. $E_{av,bw}$ will decrease at each height when moving away from the façade. For L1, the ranges of $E_{av,bw}$ on five planes are 3.2~10.2lux (VP10m), 2.0~4.77lux (VP20m), 1.3~2.35lux (VP30m), 0.86~1.36lux (VP40m), and 0.6~0.87lux (VP50m). However, with higher $E_{av,bw}$ at each position, L2 has the ranges 9.7~20.88lux (VP10m), 6.0~10.12lux

(VP20m), 3.73~5.31lux (VP30m), 2.38~3.11lux (VP40m), and 1.49~1.99lux (VP50m). On the planes near the façade (10m and 20m), a varying trend can be found along the height: when moving downward from the level of the building top, $E_{av,bw}$ will rise and peak at the bottom half of the façade, and then go down. L1 sees the peak positions at 6.3m (VP10m) and 4.7m (VP20m). The positions of L2 are higher: 9.4m (VP10m) and 6.3m (VP20m).

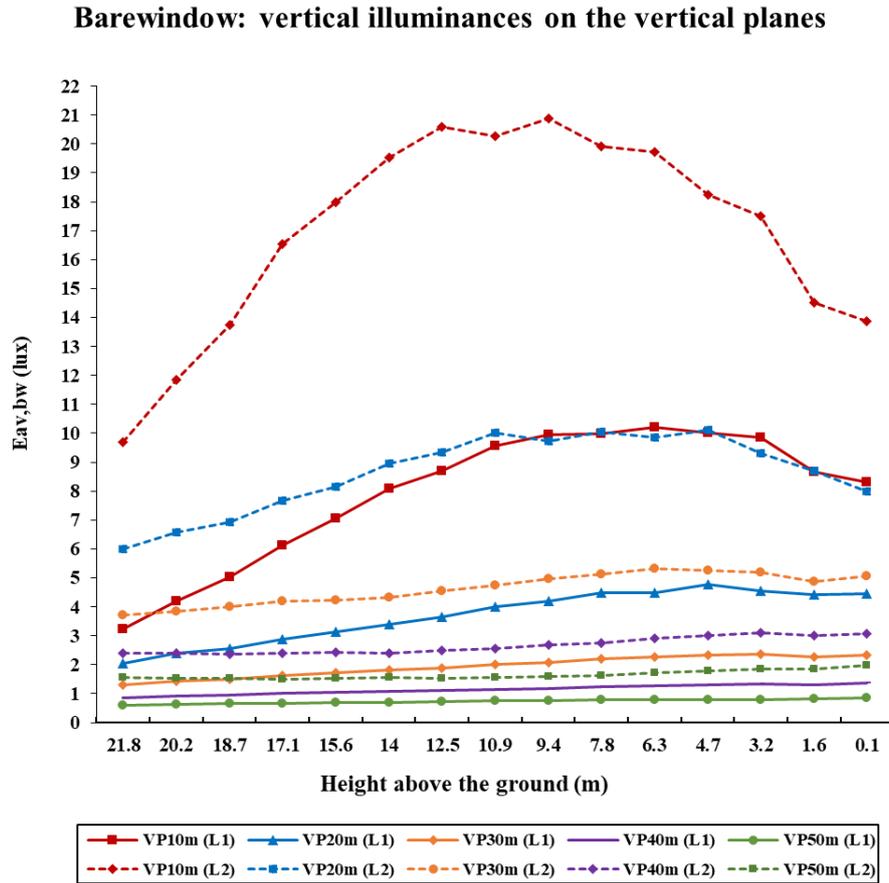


Figure 5. With the L1 and L2 system, the variations of average vertical illuminance of Barewindow ($E_{av,bw}$) on external vertical planes (VP10m – 50m).

In Figures 6 and 7, variations of relative difference of average vertical illuminance of six shading devices (R_{ve}) are given for L1 and L2 respectively. It can be clearly found that most R_{ve} values are above zero, while their varying ranges decrease with an increasing horizontal distance to the façade. These expose that most vertical illuminances of shading devices are lower than the Barewindow, and the differences will be lower with a larger distance. On each VP, R_{ve} generally tends to go up when moving toward the ground, and meanwhile divergences of R_{ve} between shading devices also become bigger. Lower positions can see greater differences of illuminances. However, such variations become unclear at the farthest plane of VP50m.

For L1 (Figure 6), first, Hlouvre and Lightshelf have the highest R_{ve} , especially on the VP of 10m, 20m, and 30m. The $R_{ve} > 10\%$ occurs at the height of 12.5m (VP10m), 10.9m (VP20m), and 6.3m (VP30m). Second, compared with Hlouvre and Lightshelf, Overhang18 has similar R_{ve} values on VP10m, and relatively lower R_{ve} values on other planes. Its $R_{ve} > 10\%$ can be found at positions of 9.4m (VP10m), 6.3m (VP20m), and 1.6m (VP30m). Third, R_{ve} values of both Overhang12 and Vlouvre are smaller than Overhang18 (the value $> 10\%$ can be only found at bottom positions of VP10m and 20m, while Overhang06 brings in the lowest R_{ve} (all values $\leq 10\%$). In general, Vlouvre will not bring in significant differences of R_{ve} on each VP.

Similarly, given L2 (Figure 7), Hlouvre and Lightshelf generally have larger R_{ve} values than other devices on the five VP. No R_{ve} of Overhang06 can be found above 10%, while Vlouvre achieves the same trend except for VP10m. The R_{ve} value $> 10\%$ can be found on all planes for Lightshelf and Hlouvre, especially at lower heights. On VP10m, Vlouvre can see the $R_{ve} > 10\%$ at all heights, whilst only lower heights bring in larger R_{ve} for Overhang18 and Overhang12. With a decreasing height, an increasing divergence of R_{ve} is found for Overhang12, Overhang18, and Lightshelf. Vlouvre and Overhang06 have no big differences of R_{ve} between various positions. Different from L1, R_{ve} variations of Hlouvre with L2 are relatively complicated. Hlouvre has a similar varying trend as Lightshelf on VP10m. However, there are big R_{ve} differences between Hlouvre and other shading devices at top and bottom façade heights on VP30m, 40m, and 50m. In addition, VP20m only sees clear divergences at the top façade heights.

For both L1 and L2, as discussed above, Hlouvre and Lightshelf can deliver the lowest illuminances at vertical planes, whereas Overhang06 and Vlouvre will not clearly affect external vertical illuminances. However, Overhang12 and Overhang18 have a medium level of such effects. With L1 and L2, significant effects of Hlouvre and Lightshelf on illuminances can be found at lower façade heights. L2 can also see a clear impact of Hlouvre at the top façade.

Shading Devices: relative differences of vertical illuminance on vertical planes (L1)

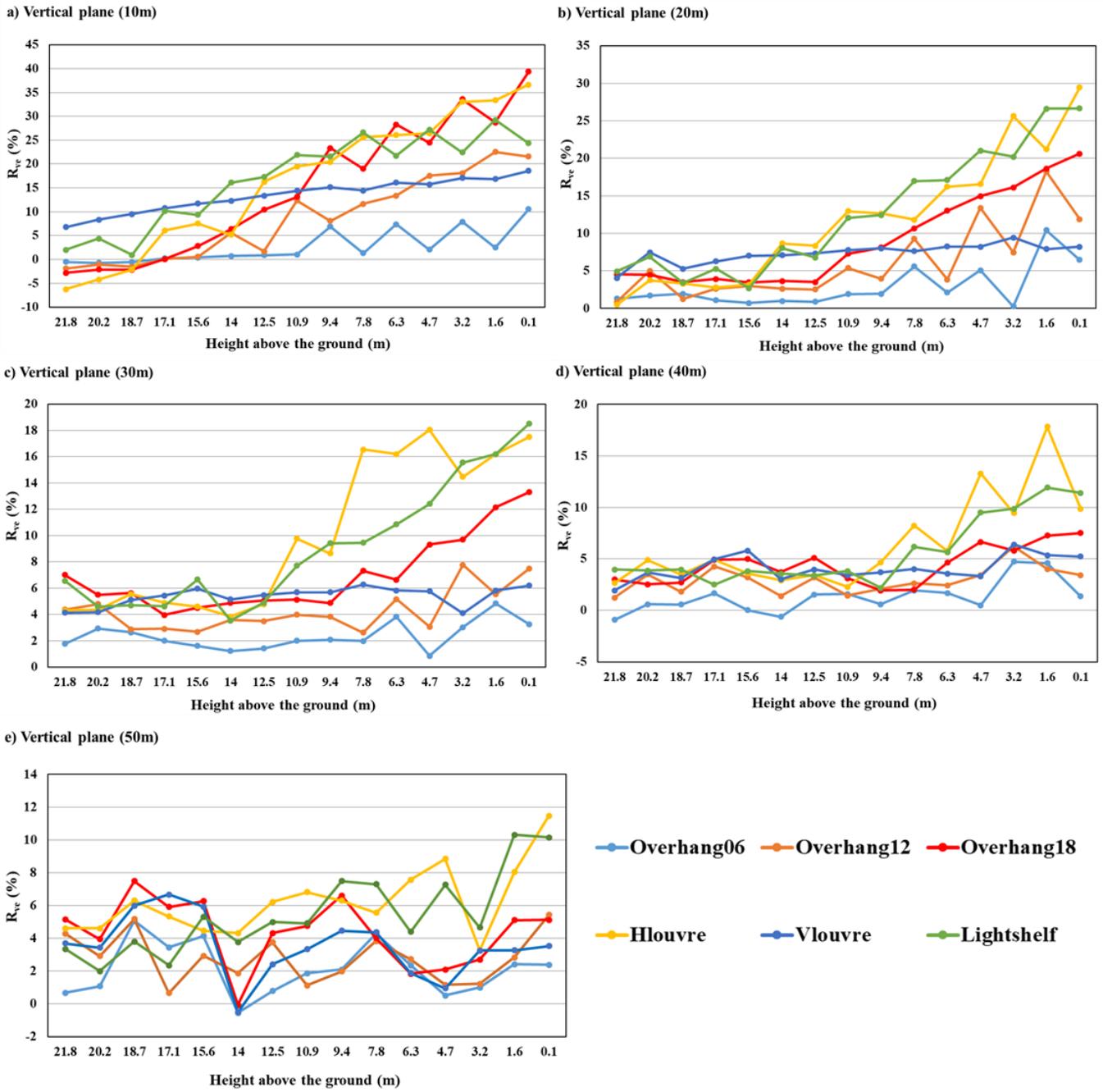


Figure 6. With the L1 system, the varying relative differences of vertical illuminance of six shading devices (R_{ve} ; taking Barewindow as the reference) on five external vertical planes (VP10m – 50m).

Shading Devices: relative differences of vertical illuminance on vertical planes (L2)

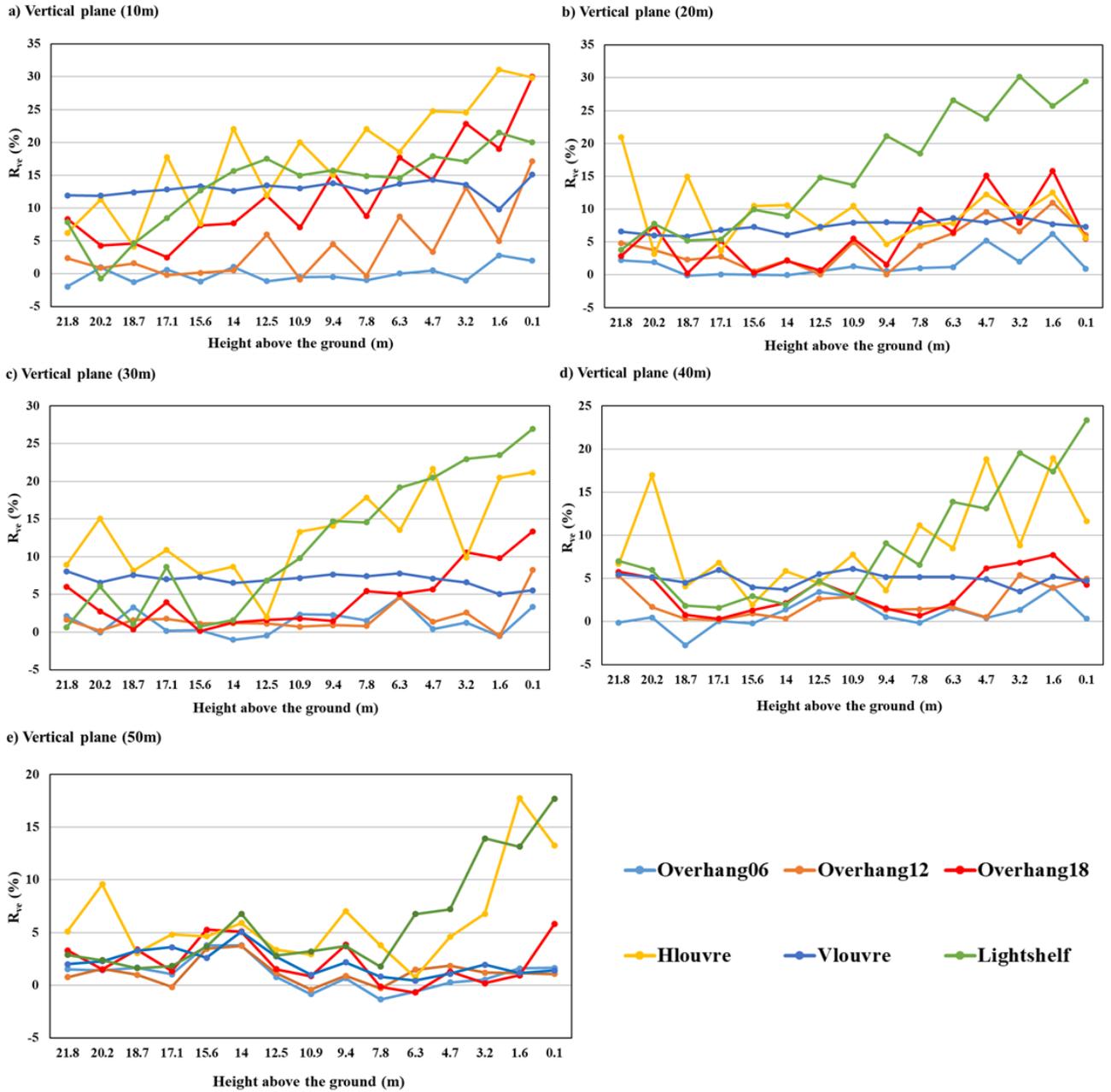


Figure 7. With the L2 system, the varying relative differences of vertical illuminance of six shading devices (R_{ve} ; taking Barewindow as the reference) on five external vertical planes (VP10m–50m).

3.1.2 Average illuminances on vertical planes

Table 1 shows AVE values on five VP with L1 and L2. Each AVE of L2 is much higher than that of L1. This supports the fact that using L2, more light can be delivered to vertical planes from the interior. Increasing the horizontal distance from the façade will significantly reduce AVE. In contrast to the Barewindow, in general, shading devices lead to a lower AVE. The biggest reduction of AVE can be found for Lightshelf and Hlouvre, while Overhang06 has the lowest impact on the reduction. The effects of other devices are in between. With the position moving away from façade, normally, the AVE of each shading solution would decrease significantly; while AVE differences between each shading device and Barewindow will be reduced.

Table 1. Average vertical illuminance (AVE) across different areas of vertical planes with various shading solutions (L1 and L2).

AVE on vertical planes (Lux)										
	VP (10m)		VP (20m)		VP (30m)		VP (40m)		VP (50m)	
	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2
Barewindow	7.93	17.01	3.70	8.62	1.94	4.63	1.14	2.66	0.74	1.65
Overhang06	7.67	17.00	3.58	8.49	1.90	4.56	1.12	2.64	0.72	1.63
Overhang12	7.11	16.30	3.45	8.24	1.86	4.54	1.11	2.60	0.72	1.63
Overhang18	6.52	14.92	3.32	8.11	1.80	4.40	1.09	2.57	0.71	1.61
Hlouvre	6.38	13.90	3.20	7.83	1.73	4.02	1.06	2.42	0.69	1.54
Vlouvre	6.80	14.77	3.42	7.98	1.84	4.31	1.09	2.53	0.71	1.61
Lightshelf	6.40	14.59	3.17	7.14	1.75	4.04	1.07	2.41	0.70	1.54

3.2 Illuminance variations on the horizontal plane

To evaluate the differences of illuminance on the horizontal plane, between shaded and unshaded models, a value R_{he} was defined as follows:

$$R_{he}(k) = \frac{E_{ah,bw}(k) - E_{ah,sh}(k)}{E_{ah,bw}(k)} \times 100\% \quad (5)$$

$$E_{ah,bw}(k) = \frac{\sum_{i=1}^{11} HE_{bw}(i,k)}{11} \quad (6)$$

$$E_{ah,sh}(k) = \frac{\sum_{i=1}^{11} HE_{sh}(i,k)}{11} \quad (7),$$

where, $R_{he}(k)$ is the relative difference of average horizontal illuminance at the horizontal position (k) between models with Barewindow and shading devices (unitless);

$E_{ah,bw}(k)$ and $E_{ah,sh}(k)$ are the average horizontal illuminance of 11 horizontal positions (i) at the position (k) for the models with Barewindow and shading devices respectively (lux);

$HE_{bw}(i, k)$ and $HE_{sh}(i, k)$ are the horizontal illuminance at the position (i, k) for the models with Barewindow and shading devices respectively (lux);

i, k are the positions of horizontal plane with Grid Distribution 1 and 2 respectively (Figure 4 [b]), $i= 1, 2, \dots, 11, k= 1, 2, \dots, 25$.

Also, the average horizontal illuminance (AHE) of all positions across each area (Area 1–5, Figure 4[b]) at the horizontal plane was calculated by the following equation:

$$AHE = \frac{HE(i,k)}{11 \times 5} \quad (8),$$

where, HE (i, k) is the horizontal illuminance at the position (i, k) of the horizontal plane.

3.2.1 Variations in horizontal illuminances along the length of plane

Figure 8 shows variations of average horizontal illuminance of Barewindow ($E_{ah,bw}$) at 25 positions of the external horizontal plane with L1 and L2.

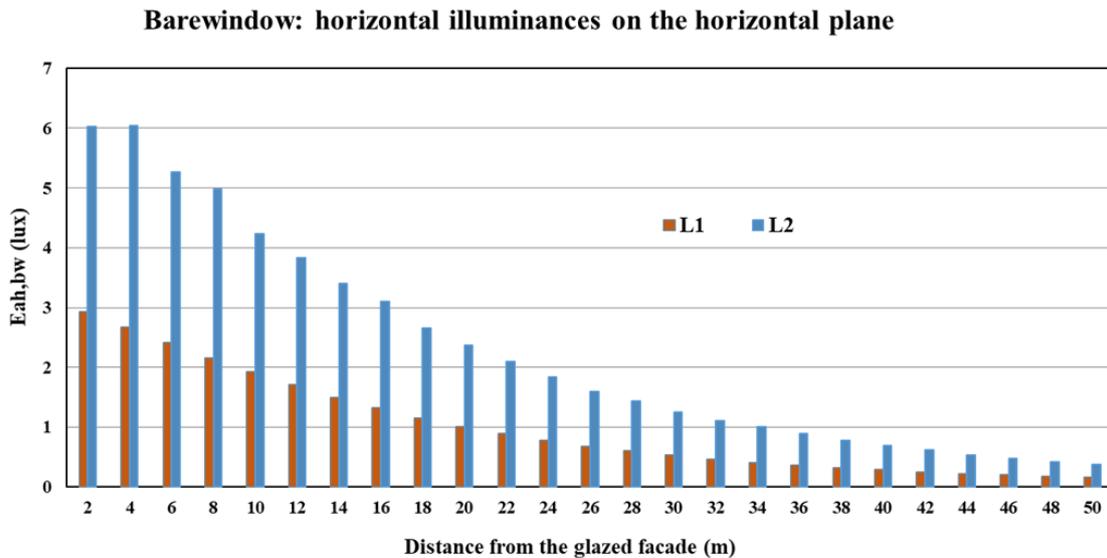
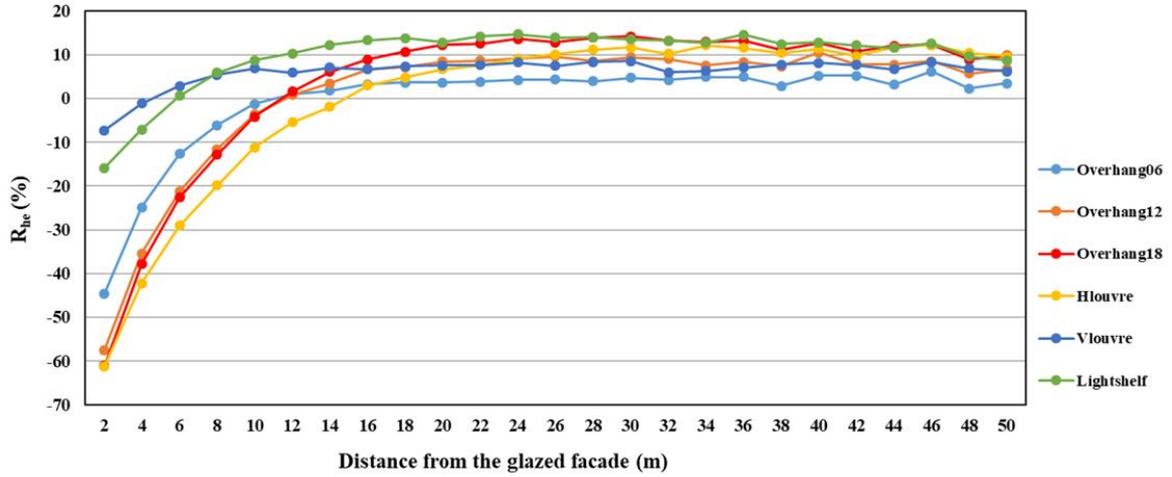


Figure 8. With the L1 and L2 systems, the variations of average horizontal illuminance of the Barewindow ($E_{ah,bw}$) on the external horizontal plane.

For L1 and L2, $E_{ah,bw}$ significantly decreases with an increasing horizontal distance from the façade. An exponential trend could be used to justify the variations. For L1, the range of $E_{ah,bw}$ is 0~3lux, while L2 has one of 0~6.1lux. The horizontal plane receives much higher illuminances with L2 than with L1, especially at positions near the façade. If taking 1lux as a reference, L1 and L2 see a lower $E_{ah,bw}$ when distance from the façade is greater than 20m or 34m, respectively. Within the distance of 4m, $E_{ah,bw}$ will not clearly vary in positions.

Shading Devices: relative differences of horizontal illuminance on the horizontal plane (L1 & L2)

a) L1



b) L2

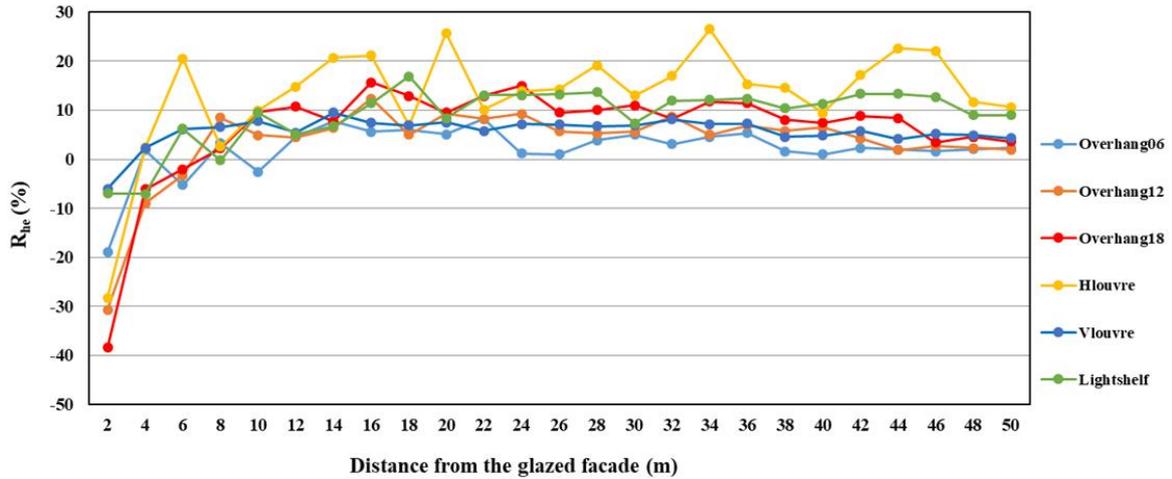


Figure 9. With the L1 and L2 system, the varying relative differences of horizontal illuminance of six shading devices (R_{hic} ; taking Barewindow as the reference) on the external horizontal plane.

Figure 9 displays variations of relative difference of the average horizontal illuminance of six shading devices (R_{he}) with L1 and L2. For L1 (Figure 9[a]), a general variation is found as: R_{he} goes up with the increasing distance to façade, and then achieves a plateau at around 20m. The positions near the façade see negative R_{he} values, indicating that shading devices can deliver higher illuminances than Barewindow. This situation occurs for Vlouvre and Lightshelf with a distance of <6m, for Hlouvre with the distance <16m, and for three overhangs with the distance <12m. Within the distance of 20m, a clear divergence of R_{he} can be found between shading devices. Vlouvre and Lightshelf have the lowest absolute R_{he} , whilst Hlouvre brings in the highest value. Overhang12 and Overhang18 have similar absolute R_{he} values, which are slightly lower than Hlouvre. In addition, absolute R_{he} values of Overhang06 are lower than other overhangs but tend to be higher than Vlouvre and Lightshelf. When the distance >16m, most of the R_{he} values are less than 10%. This indicates that shading devices will have no big impact on horizontal illuminances. Similarly, for L2 (Figure 9[b]), there is no clear influence on illuminances found in shading devices with a distance of >8m, except for Hlouvre. However, within the distance of 8m, R_{he} values tend to be negatively increased when moving towards the façade. At a distance of 2m, Hlouvre and three overhangs have a larger negative R_{he} value ($\leq -20\%$). These express that more light can be delivered upwards by them than Barewindow. Interestingly, Hlouvre can achieve a R_{he} value $\geq 20\%$ at several positions, such as 6m, 14m, 16m, 20m, etc. This explains that it will deliver less upward light than Barewindow at positions with a larger distance.

3.2.2 Average illuminances on the horizontal plane

Table 2 presents average horizontal illuminance (AHE) across five areas of the horizontal plane with L1 and L2. For L1, it is evident that only Areas 1 and 2 have significant differences of AHE between Barewindow and shading devices. At Area1, shading devices give rise to higher AHE than Barewindow, while Vlouvre and Lightshelf can achieve similar values as Barewindow. Area 2 only sees a clear difference of AHE between Lightshelf and Barewindow. Across the total area of the horizontal plane, AHE values of three overhangs and Hlouvre are relatively higher than Barewindow, while Vlouvre and Lightshelf see slightly lower AHE. Compared with Barewindow, for L2, Hlouvre and Lightshelf have no clear difference of AHE at Area 1. However, this area sees the larger AHE values for overhangs and the smaller AHE values for Vlouvre. In Areas 2 and 3, significant differences of AHE from Barewindow can be found for Overhang18, Hlouvre, and Lightshelf. Across the total horizontal plane, only Hlouvre, Vlouvre, and Lightshelf have a significantly lower AHE than Barewindow.

Table 2. Average horizontal illuminance (AHE) across different areas of the horizontal plane with various shading solutions (L1 and L2).

AHE on the horizontal plane (Lux)												
	Area1		Area2		Area3		Area4		Area5		Total Area	
	L1	L2	L1	L2								
Barewindow	2.42	5.31	1.33	3.07	0.69	1.64	0.37	0.90	0.20	0.48	1.00	2.28
Overhang06	2.90	5.56	1.30	2.89	0.66	1.58	0.35	0.87	0.19	0.47	1.08	2.27
Overhang12	3.11	5.70	1.27	2.85	0.63	1.53	0.33	0.84	0.19	0.47	1.11	2.28
Overhang18	3.16	5.77	1.24	2.73	0.60	1.45	0.32	0.81	0.18	0.46	1.10	2.24
Hlouvre	3.27	5.30	1.33	2.53	0.63	1.42	0.32	0.74	0.18	0.40	1.15	2.08
Vlouvre	2.40	5.16	1.24	2.85	0.64	1.53	0.34	0.84	0.19	0.46	0.96	2.17
Lightshelf	2.49	5.34	1.17	2.79	0.60	1.44	0.32	0.79	0.18	0.43	0.95	2.16

3.3. Illuminance variations on the side plane

Based on the aim to effectively display variations of illuminance at the side plane between shaded and unshaded models, two values of R_{se1} and R_{se2} were calculated as follows:

$$R_{se1}(k) = \frac{E_{as,bw}(k) - E_{as,sh}(k)}{E_{as,bw}(k)} \times 100\% \quad (9)$$

$$E_{as,bw}(k) = \frac{\sum_{j=1}^{15} SE_{bw}(k,j)}{15} \quad (10)$$

$$E_{as,sh}(k) = \frac{\sum_{j=1}^{15} SE_{sh}(k,j)}{15} \quad (11)$$

$$R_{se2}(k, j) = \frac{SE_{bw}(k,j) - SE_{sh}(k,j)}{SE_{bw}(k,j)} \times 100\% \quad (12), \text{ where, } R_{se1}(k) \text{ is the relative}$$

difference of average vertical illuminance at the horizontal position k between models with Barewindow and shading devices (unitless);

$E_{as,bw}(k)$ and $E_{as,sh}(k)$ are the average vertical illuminance of 15 vertical positions (j) at the horizontal position (k) for the model with Barewindow and shading devices respectively (lux);

$SE_{bw}(k, j)$ and $SE_{sh}(k, j)$ are the vertical illuminances at the position (k, j) of the side plane for the model with Barewindow and shading devices respectively (lux);

$R_{se2}(k, j)$ is the relative difference of vertical illuminance at the position (k, j) of the side plane between models with Barewindow and shading devices (unitless);

k, j are the positions of side plane with Grid Distribution 2 and 3 respectively (Figure 4 [b]), $k= 1, 2, \dots, 25, j= 1, 2, \dots, 15$.

The average vertical illuminance (ASE) of each area (Area 1–5, Figure 4[b]) on the side plane was calculated by the following equation: $ASE = \frac{SE(k,j)}{25 \times 15}$ (13), where SE (k, j) is the vertical illuminance at the position (k, j) of the side plane.

3.3.1 Variations in vertical illuminances along the length of plane

With L1 and L2, Figure 10 gives variations of vertical illuminances of Barewindow on the side plane, including average values of 15 vertical positions (E_{as}), and three values (SE) at top, middle, and ground floors (20.2m, 10.9m, and 1.6m above ground). Similar to the horizontal plane, both E_{as} and SE vary in exponential decay at the side plane. Across the side plane, E_{as} of L1 has a range of 0~6lux, while the range for L2 is 0~12lux. In general, L2 has both values of E_{as} and SE larger than those of L1. For L1, values of SE at the middle floor are similar to those at the ground floor. The top floor has lower SE values than both middle and ground floors, in particular for positions near the façade. However, L2 sees a different trend: SE (middle floor) > SE (ground floor) > SE (top floor). It seems that the middle and ground floors receive more light flux emitting from the room than the top floor at the side plane.

Barewindow: vertical illuminances on the side plane

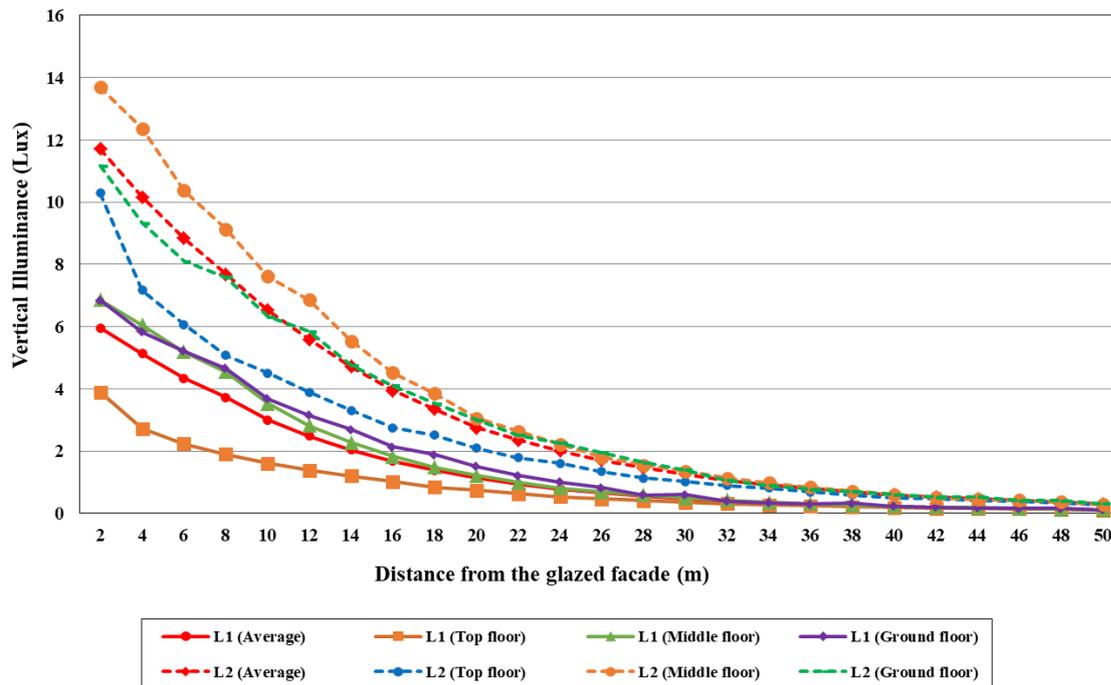
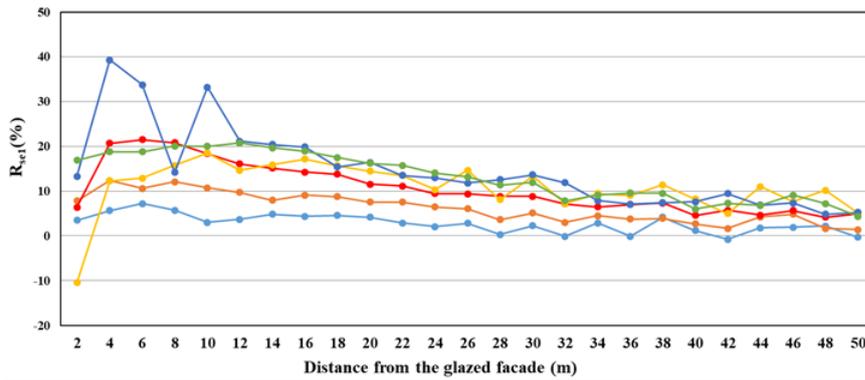


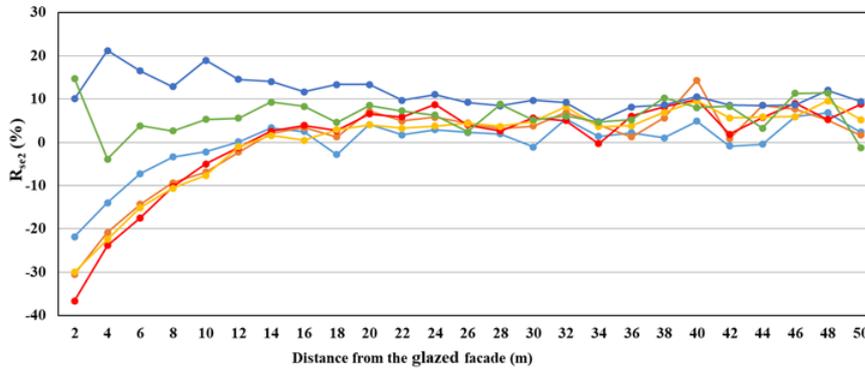
Figure 10: With the L1 and L2 system, the variations of vertical illuminance of Barewindow on the external side plane (including the average $E_{as,bw}$ and three vertical illuminances at top, middle and ground floors).

Shading Devices: relative differences of vertical illuminance on the side plane (L1)

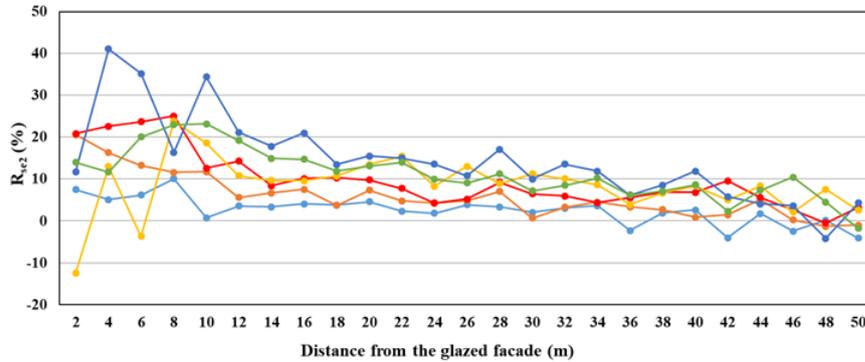
a) Side plane (average)



b) Top floor



c) Middle floor



d) Ground floor)

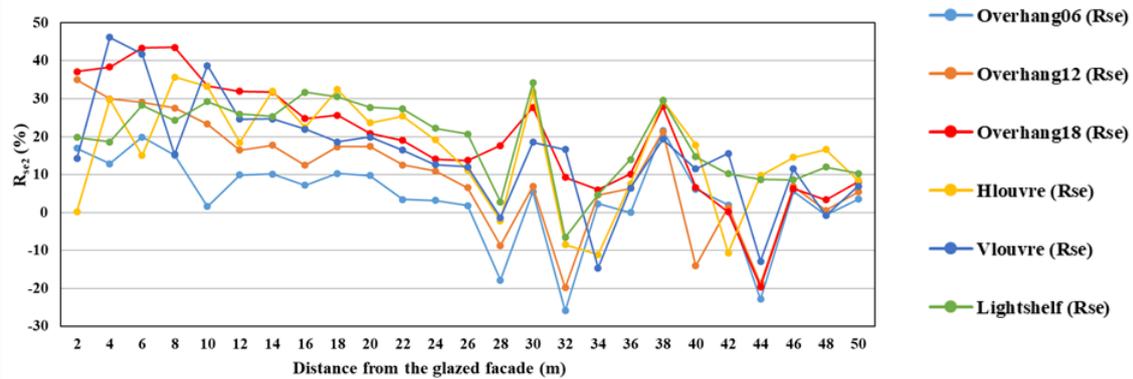
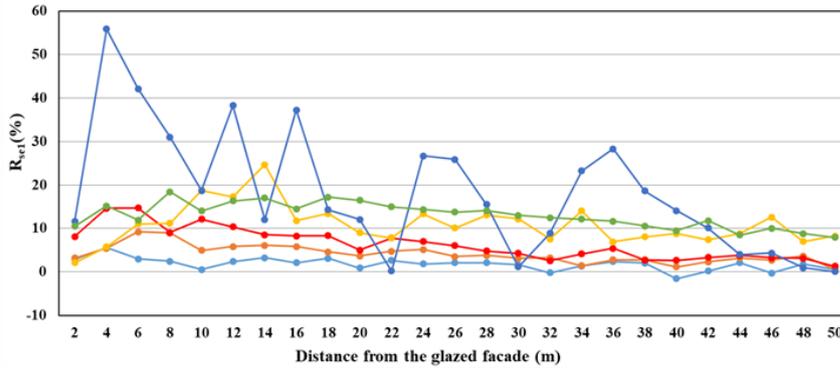


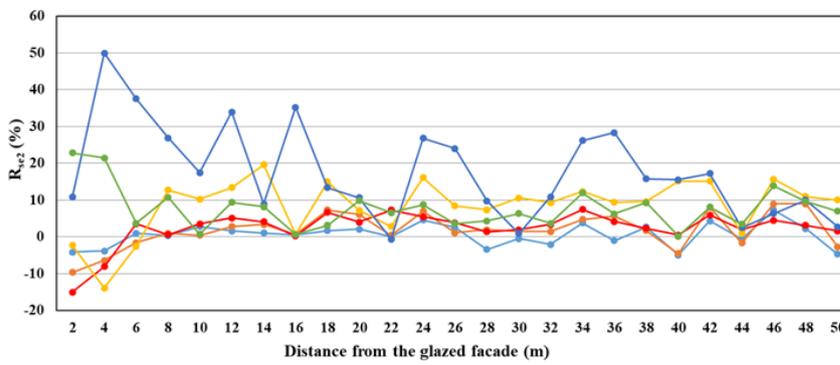
Figure 11: With the L1 system, the varying relative differences of vertical illuminance of six shading devices (taking Barewindow as the reference) on the side plane; a): R_{se1} ; b), c), d): R_{se2} at the top, middle, and ground floors.

Shading Devices: relative differences of vertical illuminance on the side plane (L2)

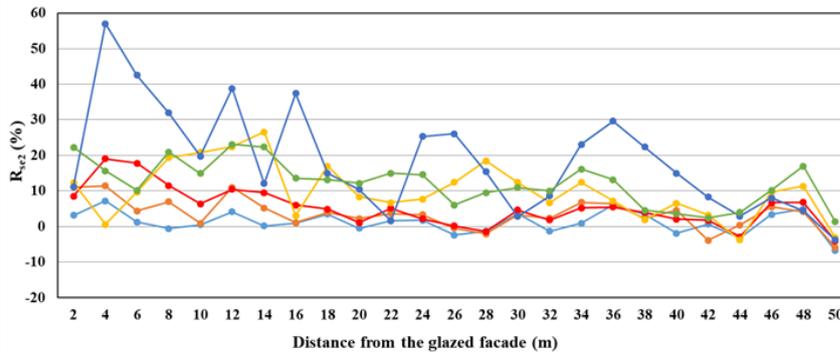
a) Side plane (average)



b) Top floor



c) Middle floor



d) Ground floor

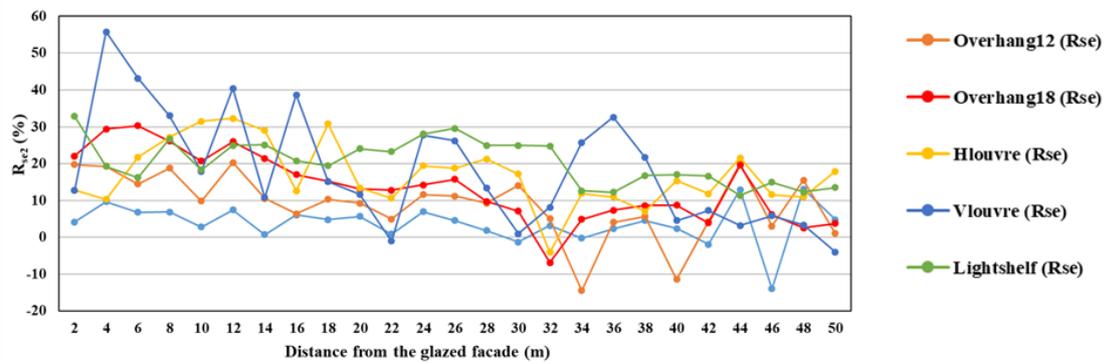


Figure 12: With the L2 system, the varying relative differences of vertical illuminance of six shading devices (taking Barewindow as the reference) on the side plane; a) R_{se1} ; b), c), d): R_{se2} at the top, middle, and ground floors.

Figures 11 and 12 show variations of relative differences of average vertical illuminance (R_{se1}) and relative differences of vertical illuminance at the top, middle, and ground floors (R_{se2}) with L1 and L2, respectively.

For L1 (Figure 11), generally, Vlouvre has the maximum R_{se1} values while the minimum values are found in Overhang06 and Overhang12. Lightshelf also has a relatively higher R_{se1} , especially at positions near the façade. Other devices see medium R_{se1} values in between. The increasing distance from the façade will significantly reduce the divergences of R_{se1} between various devices. When distance $>30m$, all R_{se1} values tend to be less than 10%, which shows a lower difference of average vertical illuminance from Barewindow at the side plane. In terms of R_{se2} (Figure 11 (b, c, d)), various façade heights bring in different variations. At the top and middle floors, divergences of R_{se2} between shading devices achieve the maxima at the distance of 2m, and decrease with the increasing distance. Thus, the convergences of R_{se2} can be found when the distance is larger than 20m (top floor) or 30m (middle floor), which are indicated by the fact that most of R_{se2} values will fall in a range of (0~10%). At the top floor, the $R_{se2} >10\%$ can be found for Vlouvre with the distance $<22m$, and Lightshelf at the distance of 2m; whilst the $R_{se2} < -10\%$ occurs with the distance $< 10m$ for Hlouvre, Overhang18, and Overhang12, and with the distance $< 6m$ for Overhang06. However, at the middle floor, most devices achieved R_{se2} values >0 , except for the Hlouvre at 2m and 6m. The ground floor, has a more complicated variation: at positions near the façade (e.g. distance $<10m$), most R_{se2} values of shading devices are over 10%; also, this trend will still be kept within the distance range of (10~28m) for most devices excluding Overhang06; with a distance $>28m$, and several peaks and valleys of the R_{se2} variation can be found at different positions. It is clear that the ground floor cannot see the same convergences as top and middle floors.

In Figure 12 (L2), most R_{se1} values of shading devices are above zero. Generally, Vlouvre and Lightshelf can achieve the R_{se1} value $>10\%$ at most positions along the side plane. On the contrary, Overhang06 and Overhang12 only see their R_{se1} values falling in a range of 0~10%. Overhang18 has a larger R_{se1} value (i.e. $>10\%$) when the distance to façade $<12m$, while most of larger R_{se1} values ($>10\%$) of Hlouvre can be found in the distance range of 10~30m. In Figure 12(b, c, d), in general, Vlouvre and Overhang06 have the maximum and minimum R_{se2} values respectively. At positions near the façade, the top floor has negative R_{se2} values for Hlouvre and three overhangs, while both the middle and ground floors see that all R_{se2} values of shading devices are above zero. With a larger distance, Hlouvre and Lightshelf can generally see relatively higher R_{se2} values than three overhangs.

Based on the discussion of L1 and L2, obviously, Vloure and Lighshelf can block the highest level of light flux to the side plane at various heights. With a larger distance from the façade, Hlouvre and Overhang18 can deliver lower illuminances to the side plan than Barewindow. On the other hand, at positions near the façade, they will add more light flux than Barewindow on the side plane, in particular at a higher façade. There is no big difference according to this effect between Overhang06, Overhang12 and Barewindow.

3.3.2 Average illuminances on the side plane

Table 3 gives ASE across five areas of the side plane, including L1 and L2. ASE values of various shading devices are lower than those of Barewindow; whereas this trend becomes unclear at Area 4 and 5. L2 will generally achieve higher ASE at each area than L1. At Areas 1–3, most devices see clear differences of ASE from Barewindow, except for Overhang06 and Overhang12. Vlouvre and Lightshelf have the lowest ASE, while ASE values of Overhang06 and Overhang12 are the maxima. However, both Hlouvre and Overhang18 see medium ASE values in between. Thus, short and medium overhangs will bring in more light to the side than Vlouvre and Lightshelf.

Table 3. Average vertical illuminance (ASE) across different areas of the side plane with various shading solutions (L1 and L2).

ASE on the side plane (Lux)												
	Area1		Area2		Area3		Area4		Area5		Total Area	
	L1	L2	L1	L2								
Barewindow	4.43	8.98	1.74	4.07	0.68	1.76	0.30	0.81	0.15	0.41	1.46	3.20
Overhang06	4.21	8.70	1.66	3.97	0.66	1.72	0.29	0.80	0.15	0.40	1.40	3.12
Overhang12	3.96	8.43	1.59	3.85	0.64	1.68	0.29	0.79	0.15	0.39	1.32	3.03
Overhang18	3.69	7.94	1.49	3.72	0.61	1.65	0.28	0.78	0.14	0.39	1.24	2.90
Hlouvre	4.09	8.21	1.47	3.41	0.59	1.56	0.27	0.73	0.14	0.37	1.31	2.86
Vlouvre	3.27	6.11	1.41	3.07	0.59	1.51	0.27	0.66	0.14	0.39	1.14	2.35
Lightshelf	3.60	7.75	1.41	3.40	0.58	1.51	0.27	0.72	0.14	0.37	1.20	2.75

4. Discussion

Given the results above, apparently, variations of illuminance on external planes can be affected by several aspects including: indoor lighting application, façade configurations (the bare window or with various shading devices), calculation positions on the planes (justified by distance from the façade and the height above the ground).

For unshaded models (bare window), external illuminances are mainly decided by light intensity distributions of indoor luminaires. As shown in Figure 3(b), the light distribution of the L2 system will emit more light flux through the window than L1. As discussed in Section 2.2, different light intensity distributions of L1 and L2 will bring in various light distributions at the windows' surface. These could explain the higher average illuminances of L2 and various illuminance distributions found at different planes. On vertical planes, positions at middle and lower façade heights could receive the direct flux from ceilings of rooms on the same floor and higher levels, and the reflected flux from floors of rooms at lower levels and the ground, while positions at the top façade, heights could be principally affected by the flux released from rooms on the same floor. However, at horizontal and side planes, the increasing distance would gradually reduce the received light flux from the rooms to external surfaces. These could explain the varying trends of the external illuminance of three types of plane.

In shaded models, the distributions and intensities of light flux emitting from indoor spaces are 'modified' based on various configurations of shading devices. With the overhangs (Overhang06, Overhang12, and Overhang18), the light flux from luminaires and room surfaces would be reflected upward by the external board, which would increase illuminances at the horizontal plane and higher positions of the side plane near the façade, and decrease the illuminances received at the vertical planes. These effects would be significantly reduced with a smaller depth, e.g. Overhang06. With more external horizontal components, the horizontal louvre (Hlouvre) can reflect more light flux to the top horizontal and side planes than overhangs; however, this could only occur at positions near the façade (e.g. the distance <6m). Thus, the vertical planes and the horizontal plane with a larger distance to the façade would receive less light flux than when using Hlouvre. On the other hand, the densely distributed external louvres would also block the light flux coming from the room. Combined with different light intensity distributions of L1 and L2, these could justify the illuminance variations brought by Hlouvre. Different from the overhang and horizontal louvre, the light shelf has both internal and external components with the same depth [44]. The internal component can efficiently 'shade' the direct light from ceiling and the reflected light from indoor surfaces at higher levels, while the external component helps to reflect the flux upwards or downwards. However, in terms of such configurations [44], it is clear that the bottom surface of the external component can

redirect more flux downwards than the flux reflected upward by its top surface. Therefore, compared with other devices, the light flux emitting from the room could be limited to a lower level at all planes with the light shelf. With a special vertical configuration, obviously, the vertical louvre (Vlouvre) can mostly block the light flux redirected to the side planes but allow it to be delivered toward the horizontal and vertical planes.

5. Conclusions

Several findings could be achieved from results and discussion above as follows: 1) A 'shining' façade with large glazing might be a source of light pollution or obtrusive light (sky glow and light trespass) at night, due to nightscape and security requirements. Directly linked with indoor lighting applications, a significant illuminance level can be found at vertical and horizontal external surfaces near the façade. External positions at middle and lower façade heights can be impacted more than by indoor lighting than positions at higher levels, while significant effects can be found within a distance of 20m to the façade; 2) Applications of shading devices can significantly take the impact on external illuminances, especially at positions with medium and lower façade heights and within the 20m distance to the façade. The large overhang (depth $\geq 1.2\text{m}$) could lower the risk of light trespass through reducing external vertical illuminances but would cause the deterioration of sky glow with the increased upward light flux. Compared with overhangs, the horizontal louvre could be more suitable for reducing the risk of light trespass; whereas more upward light flux would be produced at the same time. The vertical louvre would not generally perform well in terms of the protection of light trespass and sky glow, but it can effectively block the light flux redirected to the side. The light shelf has been popularly chosen due to its good daylighting performance [33, 44]. This study would apparently support its applications based on the new finding that the light shelf can significantly reduce the light flux emitting from the interior, which we believe can make contribution to the protection of light trespass and sky glow.

Limitations and future work: These conclusions are obviously limited to specific shading devices (as shown in Figure 2), building geometries (open-plan office in Figure 2), and lighting systems (two typical office luminaires in Figure 3). Parameters relevant to a broader range of architectural settings and lighting applications will be the subject of future work, including more room sizes, façade configurations (advanced shading/daylighting devices and glazing systems), indoor lighting systems (indirect lighting, task lighting, smart lighting controls, etc.) and controls (dimming, zoning, etc.).

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

- [1] Navara KJ and Nelson RJ. The dark side of light at night: physiological, epidemiological, and ecological consequences. *Journal of Pineal Research* 2007; 43:215–224.
- [2] Falchi F, Cinzano P, Elvidge C D, Keith D M, Haim A. Limiting the impact of light pollution on human health, environment and stellar visibility. *Journal of Environmental Management* 2011; 92: 2714-2722.
- [3] Longcore T, Rich C. Ecological light pollution. *Journal of Frontiers in Ecology and the Environment* 2004; 2: 191-198.
- [4] The Royal Commission on Environmental Pollution. *Artificial Light in the Environment*. TSO, London, 2009.
- [5] Pauley SM. Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue. *Journal of Medical Hypotheses* 2004; 63: 588-596.
- [6] Kerenyia NA, Pandulaa E, Feuera G. Why the incidence of cancer is increasing: the role of 'light pollution'. *Medical Hypotheses* 1990; 33: 75-78.
- [7] IDA (International Dark-sky Association). *Practical Guide: Introduction to Light Pollution (PG1)*. www.darksky.org; 2015. Final access: 06/05/2015.
- [8] SLL (The Society of Light and Lighting). *Guide to limiting obtrusive light*. Lavenham, Suffolk, England. 2012.
- [9] LRC (Lighting Research Centre). *Lighting answers: lighting pollution*. Troy, New York, USA. 2007.
- [10] The Royal Commission on Environmental Pollution. *Artificial Light in the Environment*. Surrey, UK. 2009.
- [11] Institution of Lighting Professionals. *Guidance Notes for the Reduction of Obtrusive Light GN01*. Rugby, UK. 2011.
- [12] CIE (The International Commission on Illumination). *Guidelines for Minimizing Sky Glow (CIE 126-1997)*. Vienna, Austria. 1997.
- [13] CIE (The International Commission on Illumination). *Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations (CIE 150-2003)*. Vienna, Austria. 2003.

- [14] IESNA (Illuminating Engineering Society of North America) & IDA (International Dark-sky Association). Model Lighting Ordinance (MLO) – 2011, with Users’ Guide. USA. 2011. <http://www.darksky.org/our-work/public-policy/mlo/>; final access: 01/05/2017.
- [15] ILP (Institute of Lighting Professionals). Guidance Notes for the Reduction of Obtrusive Light GN01:2011. UK. 2011.
- [16] SLL (Society of Light and Lighting). Guide to Limiting Obtrusive Light. London, UK, 2012.
- [17] CIE (The International Commission on Illumination). Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition (CIE 150-2017). Vienna, Austria. 2017.
- [18] IESNA (Illuminating Engineering Society of North America). TM-15–11: Luminaire Classification System for Outdoor Luminaires. New York, 2011.
- [19] Chinnis D, Mutmansky M & Clanton N. IES TM-15 BUG Value-Setting and Adjustment Methodology. LEUKOS: The Journal of the Illuminating Engineering Society of North America 2011; 8(1): 25-39.
- [20] Cabello A.J & Kirschbaum C.F. Modeling of Urban Light Pollution: Seasonal and Environmental Influence. Journal of the Illuminating Engineering Society 2001; 30(2): 142-151.
- [21] Saraiji R & Oommen M.S. Light Pollution Index (LPI): An Integrated Approach to Study Light Pollution with Street Lighting and Façade Lighting. LEUKOS: The Journal of the Illuminating Engineering Society of North America 2012; 9(2): 127-145.
- [22] Ko T.K, Kim I.T, Choi A.S, Sung M.K. Quantitative Assessment Methods for Determining Luminous Environmental Zones in Korea. Lighting Research & Technology 2014; 48: 307-322.
- [23] Ho C.Y & Lin H.T. Analysis of and Control Policies for Light Pollution from Advertising Signs in Taiwan. Lighting Research & Technology 2015; 47: 931-944.
- [24] Garvey P.M. On-Premise Commercial Sign Lighting and Light Pollution. LEUKOS: The Journal of the Illuminating Engineering Society of North America 2005, 1(3): 7-18.
- [25] Bullough J.D, Brons J.A, Qi R & Rea M.S. Predicting Discomfort Glare from Outdoor Lighting Installations. Lighting Research & Technology 2008; 40: 225-242.
- [26] De Boer JB. Visual perception in road traffic and the field of vision of the motorist. In De Boer JB, editor, Public Lighting. Eindhoven Philips Technical Library, 1967, 11–96.
- [27] Sim Y.J, Kim I.T, Choi A.S & Sung M.K. A Preliminary Study of an Evaluation Method for Discomfort Glare Due to Light Trespass. Lighting Research & Technology 2017; 49: 632-650.
- [28] Brons J.A., Bullough J.D. and Rea M.S. Outdoor site-lighting performance: A comprehensive and quantitative framework for assessing light pollution. Lighting Research & Technology 2008; 40: 201-224.

- [29] Wu F. *Planning for Growth: Urban and Regional Planning in China*. Routledge, New York, 2015.
- [30] Boyce PR. *Human Factors in Lighting*. CRC Press, Boca Raton, FL, USA, 2014.
- [31] LuxReview. *Outrage at Apple's After-hours Lighting*. 2013. Webpage link:
<http://luxreview.com/article/2013/05/outrage-at-apple-s-after-hours-lighting> (final access: 16 April 2018).
- [32] Wymelenberg KD. Patterns of occupant interaction with window blinds: A literature review. *Energy and Buildings* 2012; 51:165-176.
- [33] Xue P, Mak C.M., Cheung H.D. New static lightshelf system design of clerestory windows for Hong Kong. *Building and Environment* 2014; 72:368-376.
- [34] Manzan M, Clarich A. FAST energy and daylight optimization of an office with fixed and movable shading devices. *Building and Environment* 2017; 113:175-184.
- [35] JGJ 67, 2006, Deign code for office building. China: Ministry of Housing and Urban-Rural Development.
- [36] GB50351, 2005, Code for design of civil buildings, China: Ministry of Housing and Urban-Rural Development.
- [37] Du, J., Zhang, X., 2015. Light trespass protection in a glazed office building: how the shading system works? *Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association*. Hyderabad, India.
- [38] Wang, X., 2010. *A collection of Chinese Modern Buildings II. Office Building*. Tianjin University Press. Tianjin, China.
- [39] GB/T 50033, 2013, Standard for daylight design of buildings, China: Ministry of Housing and Urban-Rural Development.
- [40] GB/T 50034, 2013, Standard for lighting design of buildings, China: Ministry of Housing and Urban-Rural Development.
- [41] LBNL (Lawrence Berkeley National Laboratory). *International Glazing Database*. Webpage link:
<http://windowoptics.lbl.gov/data/igdb> (final access: 26 April 2018).
- [42] Esquivias P.M., Munoz C.M., Acosta I, Moreno D and Navarro J, Climate-based daylight analysis of fixed shading devices in an open-plan office. *Lighting Research and Technology* 2015; 48: 205-220.
- [43] IEA (SHC Task 21/ ECBCS Annex 29), *Daylight in buildings: a source book on daylighting system and components*. Report of Lawrence Berkeley National Laboratory. 2000. Available from:
<https://facades.lbl.gov/daylight-buildings-source-book-daylighting-systems> (final accessed 10 July 2014).

[44] Littlefair P.J. Light shelves: Computer assessment of daylighting performance. *Lighting Research and Technology* 1995; 27: 79-91.

[45] DB11/T 388.1, 2015, Technical specification of urban landscape lighting: Part1-5. Beijing Municipal Administration of Quality and Technology Supervision, Beijing, China.

[46] Speirs + Major, 2017, *Light + Darkness in the City: A Lighting Vision for the City of London*, London, UK. Available from: www.cityoflondon.gov.uk/services/environment-and-planning/city-public-realm/public-consultations/Documents/City-of-london-lighting-strategy-part-1.pdf (final accessed 7 April 2018).

[47] DIAL GmbH. DIALux evo manual. 2016. Available from: www.dial.de/fileadmin/documents/dialux/DIALux_downloads/DIALux%20evo%20manual.pdf (final accessed 10 December 2017).

[48] Ward G L & Shakespeare R. 1998. *Rendering with Radiance: The art and science of lighting visualization*. Morgan Kaufmann Publishers, Inc. San Francisco, California, USA.

[49] LBNL (Lawrence Berkeley National Laboratory). 2012. *Optics 6 Release Notes*. California, USA.