Analysis of the daylight performance of a glazing system with Parallel Slat Transparent Insulation Material (PS-TIM)

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Abstract:

Daylight plays an important role in the energy efficiency and indoor environmental quality of an office building. An innovative façade system where parallel transparent/translucent plastic slats are sandwiched between glass panes to form a Parallel Slat Transparent Insulation Material (PS-TIM) is proposed as a strategy to effectively increase the thermal resistance of window systems, while providing better daylight performance. In this paper, the optical performance (as defined by *Bidirectional Scattering Distribution Function*) of a double glazed window containing PS-TIM systems with different slat pitches (the distance between neighbouring slats), slat tilt angles, as well as the slat materials (transparent and translucent) was obtained using a ray-tracing technique. Then, the annual daylight performance of a typical office building with various PS-TIM applied under different climatic conditions and at different orientations was investigated using RADIANCE. The simulation results show that PS-TIMs with translucent slats offer better daylight performance than conventional double glazing: it can increase the percentage of annual working hours under daylight, where the illuminance lies in the useful range of up to 79%. It also achieves a homogenous distribution of daylight within the internal working space and effectively reduces the possibility of glare. When applying PS-TIM at higher site latitude, smaller slat pitches are required to maximise useful daylight. Optimised PS-TIM geometry is also affected by local prevailing sky conditions.

Keywords: Parallel Slat Transparent Insulation Material (PS-TIM); RADIANCE; daylight performance.

1. Introduction

The quantity, quality and distribution of daylight that passes through a window system and illuminates a space, plays an important role in energy efficiency and achieving a comfortable indoor environment. It influences lighting, heating and cooling energy consumption, as well as the thermal and visual comfort perceived by a building's occupants [1]. Additionally, the comfort level provided by daylighting has also been proven to affect human health, mood, activity and work efficiency [2]. Thus, a good design of window system becomes increasingly important. This requires that significant attention is given to designing an effective system that offers a balanced strategy incorporating advances in both thermal and optical thinking, as well as effective use of building prediction methods to quantify performance when applying these novel systems to buildings.

The use of Transparent Insulation Materials (TIM) sandwiched between the panes of a double-glazed window unit is proposed as a strategy for, offering the potential to increase the thermal resistance of a double glazed window, to maintain access to solar light and heat, and to provide a comfortable pattern of daylight distribution. Parallel slat TIM (PS-TIM), as illustrated in Figure 1, divides the air cavity between two glazing panes into small horizontal, linear cells. The slats themselves provide additional viscous resistance to the onset of free convection and in addition interfere with the thermal radiation transferred from one pane of the double glazed unit to the other. As demonstrated by Sun et al. [3], the employment of PS-TIM can reduce the heat transfer coefficient of a double-glazed unit, and in so doing, improve the thermal behaviour of buildings they are employed in. The employment of PS-TIM does, however, reduce the amount of daylight transmitted through the window system as well as modify the daylight distribution within the space it serves. The improved thermal insulation offered by integrating PS-TIM into windows and its effect on indoor illuminance level can ultimately affect the overall energy efficiency of the building. The daylight aspect of PS-TIM behaviour serves as the focus of this paper.

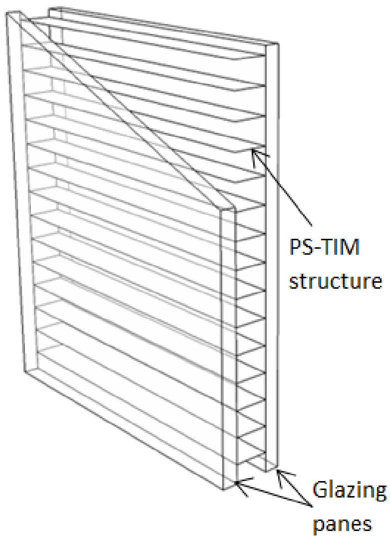

Figure 1: PS-TIM in a double glazed unit

In seeking to evaluate the quantity, quality and distribution of daylight accurately, traditional approaches, which are mainly based on the use of rule of thumb or simplified calculation methods (e.g. daylight factor (DF)) are increasingly deemed inadequate [2]. In a move to improve the objectivity and accuracy when evaluating daylight strategies, a number of new and refined metrics, such as *useful daylight illuminance* (*UDI)*, *daylight glare probability* (*DGP*) etc., have been proposed [4-6] and are becoming increasingly common in the literature [7-11]. These sophisticated metrics are evaluated using dynamic simulation tools (e.g. RADIANCE [12-15]) in conjunction with a Bidirectional Scattering Distribution Function (BSDF) to represent the optical performance of complex window systems [12, 16-18].

This paper provides a comprehensive picture of daylight performance when applying PS-TIMs to window system through the use of dynamic metrics. RADIANCE has been used to determine the dynamic daylighting performance of a notional double glazed window system with and without PS-TIM installed in a typical office, using a “Three-phase method”, commonly employed in the daylight simulation of complex fenestration systems.

In the simulation, a cellular office room with various window systems is modelled, and the illuminance distribution calculated for 1 hour time-step over the course of a year. The predicted illuminances during working hours were analysed using advanced metrics (e.g. *UDI*, *DGP* and *UR*). The influence of slat pitch (the distance between neighbouring slats), slat tilt angle, as well as the optical performance of the slat material itself for the PS-TIMs are also investigated to understand their effects on the overall daylight performance. The chosen PS-TIMs have also been investigated under different climate conditions and different building orientations to provide an indication of how site-specific variables influence performance.

It is worth noting that although PS-TIM has the potential to offer improved performance of daylight distribution, the designer would have to consider the extent to which they interrupt view out of and in to building. This study looks only at daylight behaviour and does not consider the effect that PS-TIM has on view.

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2. Daylight performance assessment metrics

The use of "rule of thumb" methods [19], such as *window area to floor area ratios* to verify the daylighting sufficiency, or calculation of *daylight factor* (*DF*), which is defined as the ratio between indoor to outdoor illuminance and can be used to estimate the adequacy of daylight provision, are wide spread throughout many countries. Although, these methods are frequently formalised within national standards and form part of the standard set of tools used by designers [2], their accuracy can be limited as they frequently fail to take into account the specificity of building site (e.g. orientation, surrounding conditions etc.), local climate and, related to this, the effect of direct sunlight [20]. When working with complex fenestration systems, which cause redirection and scattering of daylight, availability of more accurate methods and more advanced metrics becomes even more pressing. Key static metrics as well as dynamic metrics that are based on annual climate data, encompassing both daylight availability and user comfort levels in a room, are compared and summarised in Tables 1 and 2.

Table 1 Comparison of daylight metrics used in this paper

	Static metrics	Climate-based metrics	Daylight availability	Visual comfort	Included in standards or green buildings verification tools?	Description	Thresholds
Daylight factor (*DF*)	✓		✓		Yes, most of the national daylighting standards, e.g. American IESNA standards [21] and Chinese standards [22]	*DF* is a ratio of interior illuminance at a point within a building to the exterior horizontal illuminance under an unobstructed CIE overcast sky [23]	At least 2% for office spaces in most of standards
Clear sky studies on solstice and equinox days	✓		✓	✓	Yes, e.g. LEED rating system [24]	Daylighting in a space with a fenestration system under clear sky conditions at 9 am, noon and 3pm on solstice and equinox days, expressed in illuminance or luminance [20]	N/A
Useful daylight illuminance (*UDI*)		✓	✓		No	By using lower and upper thresholds, *UDI* divides the illuminance level of hours in a year into three bins [6]	*Undersupply* bin: < 100 lux *Useful* bin: 100 ~2000 lux *Oversupply* bin: > 2000 lux
Illuminance *uniformity ratio (UR)*		✓		✓	Yes, e.g. BREEAM rating system [25]	Uniformity is the ratio between maximum and minimum illuminance inside a space [26]	1:5 in CIBSE [27] 1:2.5 in BREEAM [25]
Simplified *daylight glare probability* (*DGPs*)		✓		✓	No	A simplified annual method to evaluate daylight glare based on vertical illuminance (E_v) [4, 28]: $DGPs = 6.22 \times 10^{-5} E_v + 0.184$	*Imperceptible*: ≤ 0.35 *Perceptible*: 0.35 ~ 0.4 *Disturbing*: 0.4 ~ 0.45 *Intolerable*: ≥ 0.45

Table 2: Comparison of daylight metrics used in this paper (continued)

	Advantages	Disadvantages
Daylight factor (*DF*)	• Simple to calculate • Widely used in daylight standards	• Building sites, climate, time in the day and variable sky conditions [20] are not considered • Direct solar ingress is not considered, only diffuse • Standards that do not recommend maximum *DFs* can lead to oversupply of daylight, risk of thermal discomfort and possibility of glare
Clear sky studies on solstice and equinox days	• An intuitive expression of the daylight distribution (i.e. illuminance or luminance) under different solar incident angles	• Specific climate data are not considered • Requires a large number of individual simulations and a review of multiple figures
Useful daylight illuminance (*UDI*)	• Takes into account the hours of actual operation and real weather conditions at the site • Uses an upper threshold to avoid oversupply conditions • Good for comparing the performance of different design variations	• Requires specialized experience for simulation • Time-consuming calculation since it is necessary to determine illuminance for every daylight hour over the course of a year on each study point
Illuminance *uniformity ratio (UR)*	• Gives an intuitive impression of how uniformly daylight is distributed in a space	• Requires specialized experience for simulation • Time-consuming calculation since it is necessary to determine illuminance for every daylight hour over the course of a year on each study point
Simplified *daylight glare probability* (*DGP*)	• Effective method to accumulate the probability of daylight glare for a view direction for every daylight hour in a year	• Invalid for situations where sunlight enters the occupant's direct field of view • Computationally intensive calculation

3. Simulation method

The generation of daylight performance metrics can be performed using annual hourly simulation results obtained from RADIANCE [29]. RAIDANCE is a software tool based on a backward ray-tracing algorithm, which means that the rays are emitted from the point of interest and traced backwards until they either hit a light source or another object [30]. The accuracy of this research-grade simulation tool has been validated by several studies [12-15].

For a dynamic daylight simulation of a space, hourly based annual climate data, which includes direct sunlight and diffuse skylight, are required for the daylight performance prediction. For a space illuminated via a complex fenestration system, such as PS-TIM, the multiple inter-reflections that occur within the system become a further challenge for dynamic annual simulation. Swapping these complex interactions with a pre-calculated transmission matrix, (T), which characterizes flux output as a function of input for a particular configuration of light source and receiver, provides a simple but effective description of complex fenestration system in RADIANCE [12]. In addition, a daylight matrix, (D), and a view matrix, (V), that describe the external and internal conditions respectively, may also be calculated using a modified daylight coefficient method in advance of annual simulation [16]. Flux transfer represented by these three matrices forms a “Three-phase method”, where the matrices are used in a multiple inner time-step loop with an assigned value for the sky condition (sky vector (s) or sky matrix (S)). This is proposed as a means of effectively and accurately performing annual daylight simulations of systems where complex fenestration systems are applied [12, 16, 31]. The results, which can be illuminance or luminance at any point of interest for a single time step (i) or for a time series (I), are computed using the following equations:

$$i=VTDs \tag{6-1}$$

$$I=VTDS \quad (6\text{-}2)$$

where the sky vector (*s*) is generated by dividing the whole sky into discrete patches, with each patch being assigned an average radiance value for a given time and sky condition, while the sky matrix (*S*) is a time series of sky vectors. An annual sky matrix is generated from hourly input weather data for the 8760 hours in a year.

In this research, the 'Three-phase method' was used to conduct the dynamic annual daylight simulation of PS-TIM window systems in an office. The daylight matrix and view matrix were obtained based on the model's orientation, surrounding environment, geometry and surface properties of the indoor space (details can be found in section 3.3) using an embedded command in RADIANCE. Sky matrices were obtained from IWEC (International Weather for Energy Calculation) weather data for five cities with different latitudes and climates (details can be found in section 3.2). The transmission matrix for the window systems with PS-TIM was expressed using *Bidirectional Scattering Distribution Functions* (*BSDFs*) (details can be found in section 3.1).

3.1 BSDF for a window system with PS-TIM

A *BSDF* file defines coefficients to allocate light from each exterior direction to each interior direction. In so doing, the angularly resolved transmissions and reflections for a complex window system are included in the annual calculation process. The *BSDF* based on Klems angle basis is a primary format for RADIANCE. As shown in Figure 2, it comprises 145 × 145 matrices for fenestration systems, which can account for the transformations that occur to both solar and optical spectra. Each matrix describes reflectance or transmittance distribution in the outgoing hemisphere for each incident angle of the incoming hemisphere.

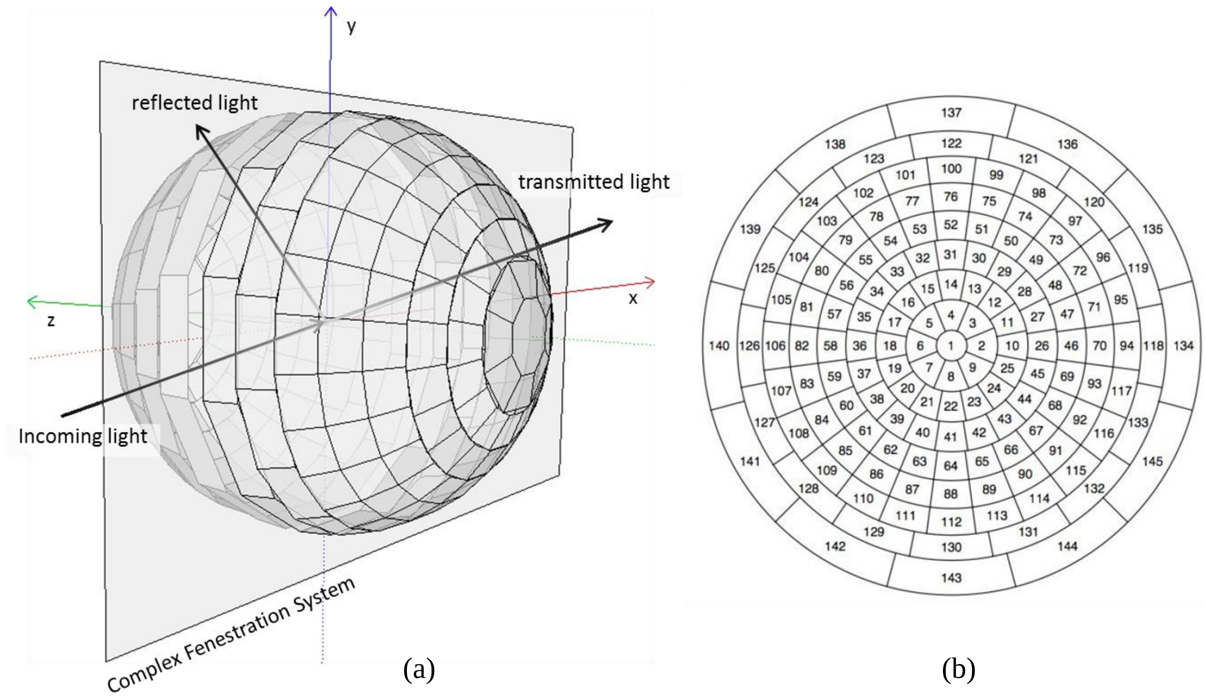
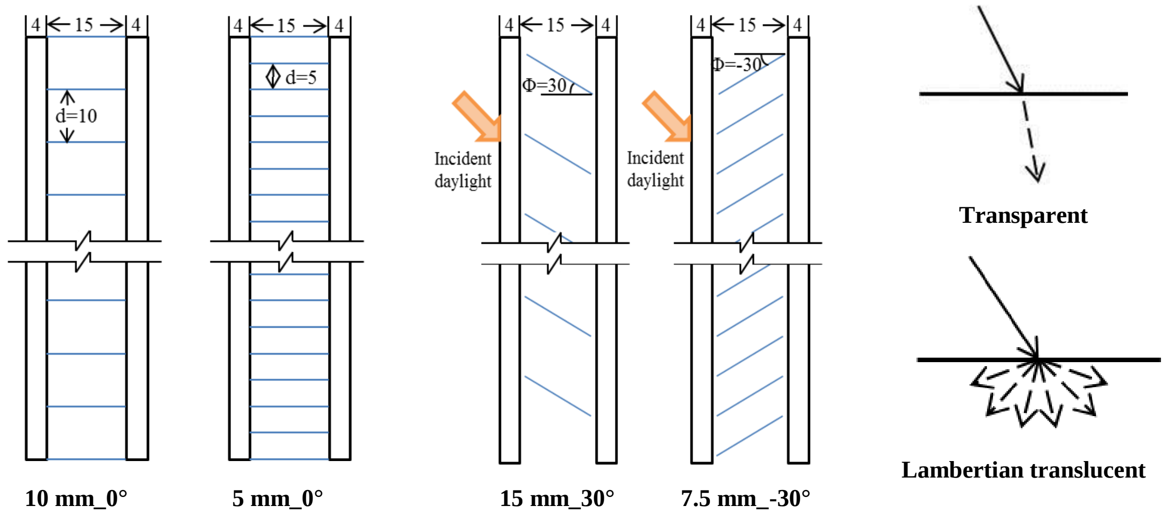


Figure 2: (a) schematic diagram of *BSDF* and (b) Klems 145-patch hemispherical basis with numbered subdivisions

The *BSDF* can be obtained by two methods: measurement using goniophotometric equipment [32-34] or calculation using validated ray-tracing methods [33-35]. A ray-tracing program genBSDF in RADIANCE [29], which has been validated by McNeil et al. [35], was used in this research to calculate *BSDF* of different interstitial PS-TIM structures based on their geometry and material properties.

The *BSDF* data was calculated by RADIANCE for PS-TIM systems with 4 slat pitches (15mm 10mm 7.5mm and 5mm), at 7 different slat orientation angles (0°, 30°, 45°, 60°, -30°, -45° and -60°) and 2 different slat materials (transparent and Lambertian diffuse translucent with 50% transmission). Examples of the investigated PS-TIM with different slat pitches are shown in Figure 3 (a), PS-TIM with different tilt angles are shown in Figure 3 (b) and PS-TIM with different slat materials are shown in Figure 3 (c).



(a) (b) (c)

Figure 3: Schematic diagram of variables: (a) slat pitch (d mm); (b) tilt angle (Φ °) and (c) slat material

3.2 Weather data

To investigate the performance of the proposed PS-TIMs under different geographical and weather conditions, five cities: Stockholm; London; Beijing; Hong Kong and Singapore were selected. The latitude, longitude and solar radiation conditions for these cities are shown in Table 3. The simulations were run at 1-hour time-steps for an entire year using IWEC weather file for the site. The diurnal direct and diffuse solar radiation of these five cities can be found in Appendix A.

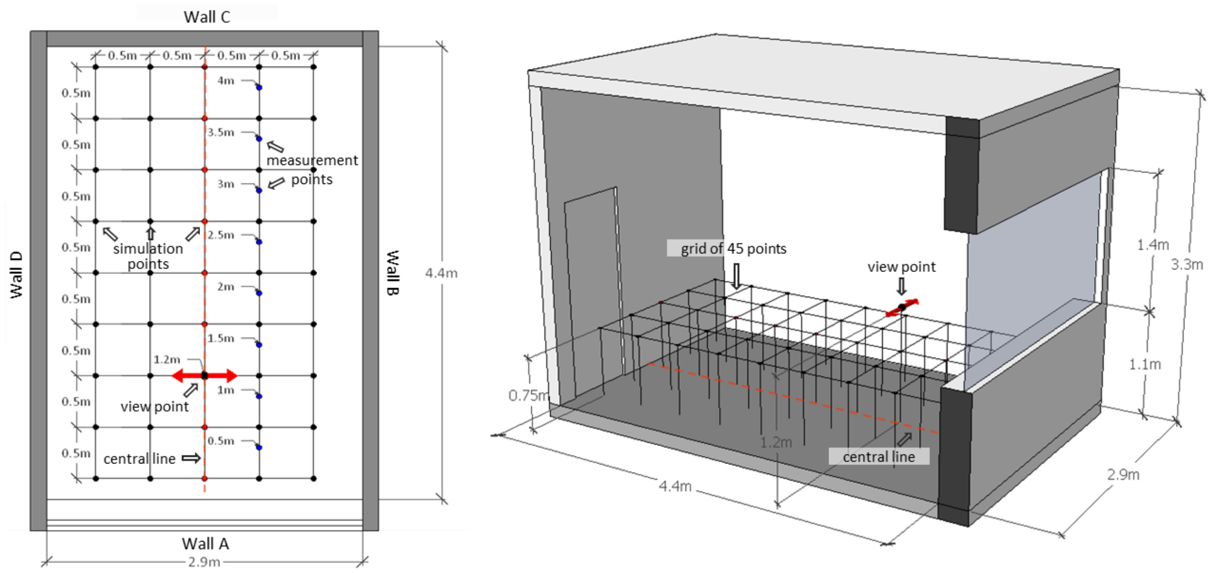
Table 3: Latitude, longitude and annual average solar irradiance for five case study cities

	Latitude	Longitude	Noon solar altitude		
			summer solstice	equinox	winter solstice
Stockholm	59.3° N	18° E	53.1°	28.7°	6.7°
London	51.5° N	0° W	62.1°	37.6°	15.2°
Beijing	39.9° N	116° E	70.7°	48.6°	25.7°
Hong Kong	22.3° N	114.2° E	77.2°	62.2°	42.5°
Singapore	1.3° N	103.8° E	67.8°	88.6°	65.2°

3.3 Model geometry and material properties

A side lit cellular office with dimensions 2.9 m (width) × 4.4 m (depth) × 3.3 m (height), which is based on a real room in the Energy Technologies Building in the University of Nottingham, UK, was chosen for the simulation. The office surfaces were treated as perfectly diffuse with typical visible reflectances of 30% (floor), 80% (walls) and 80% (ceiling). In order to clearly describe the geometry of the room, the four walls are represented by A, B, C and D as illustrated in Figure 4. A window with dimensions 1.4 m (height) × 2.9 m (width) is located in wall A with a sill height of 1.1 m above the floor. Four window orientations: South, East, West and North are considered in the studies. The original double glazed window has a visible light transmission of 78%. The furniture inside the room was modelled according to the layout of the prototype office. It was assumed there were no surrounding buildings, vegetation or other obstructions outside the office. An exterior ground with RGB reflectance of (0.4, 0.4 and 0.1) [29] was used to represent a grass green colour in the external environment. The enclosing surfaces of the room, all the furniture and exterior ground were built up directly in RADIANCE.

A 9 × 5 grid comprising 45 points at 0.5 m centres was used to estimate the illuminance distribution on a working plane positioned at a height of 0.75 m above floor level as illustrated in Figure 4. The grid was located centrally on plan, 0.2m away from wall A and C and 0.45 m away from wall B and D. The room was assumed to be used as a private office for two people, with one positioned near the window and the second at the back of the room. As glare caused by daylight is less likely to be an issue at the back of the room, the glare evaluation was based on a view point representing the occupant near the window. This was located at a distance of 1.2 m from the window and at a height of 1.2 m above the floor on the centre axis of the room; facing wall B or D.



(a) (b)

Figure 4: Selected points for evaluating illuminance distribution in the office space (a) Plan view and (b) sectional view

3.4 Simulation conditions and rendering parameters

The room is schedule assumed occupancy schedule between 8:00 and 17:00. Within this study, the following rendering parameters for RADIANCE were used:

Table 4: RADIANCE simulation parameters

Ambient bounces (-ab)	Ambient divisions (-ad)	Ambient supersamples (-as)	Ambient resolution (-ar)	Ambient accuracy (-aa)	Direct sampling (-ds)
12	50000	512	256	0.13	0.2

According to investigations undertaken by Wienold and McNeil [4, 31], these settings seem to deliver reliable values for the given scenes.

3.5 Model validation

The accuracy of the RADIANCE algorithm, daylight coefficient method and Perez sky model have been discreetly validated under over 10,000 sky conditions including overcast skies, clear skies and partly cloudy skies by Reinhart [14, 36] and Mardaljevic [37, 38]. They used the data from a sky scanner to describe the luminance distribution of the celestial hemisphere including the sun in their simulation model, and then compared the simulated results of indoor illuminance level under each sky condition with the measured results under the same condition. The results indicated a high level of reliability in the use of RADIANCE to predict the annual indoor illuminance distribution in a space based on the building geometry, optical properties of the material surfaces and direct and diffuse irradiances. In this research, to provide confidence of accurately using RADIANCE for PS-TIM prediction, the illuminances for the prototype room were measured and compared with illuminances from simulation under the same conditions. The illuminance measurement method was a simplified version of the validated method for illuminance measurement developed by Reinhart [14, 36] and Mardaljevic [37, 38]. The measurements were conducted on two overcast days in October 2015. As the sky conditions were totally overcast and there was no direct irradiance, the luminance distribution of the celestial hemisphere was assumed to be uniform in the simulation. The external non-obscured horizontal illuminance and indoor illuminances at the selected 8 measurement points (along the centre line of the room between the window and the end wall) were measured using calibrated chromameters, CL-200A (with an accuracy of ± 2% or ±1 the smallest digit of the displayed value). Comparison was made between the simulated indoor illuminance and the measured illuminance on the working plane (shown in Figure 4). The simulation assumed a typical double glazing (window without TIM) under two external illuminance levels: one with 10,000 lux and the other with 2,500 lux. In order to avoid the influence of a neighbouring building and vegetation on the measured illuminance, the study was based on an office on the top floor of the building.

Figure 5 shows a comparison between measured and simulated values. The results agree reasonably well with the greatest deviation (13.5%) occurring 0.5m away from the window when the external horizontal illuminance was 10000 lux. This is due to the presence of a small window sill and an incompletely rolled up blind near top of the window (see Figure 6), which lead to more obstruction of light near the window neither of which was considered in the simulation. A photo of the prototype office room, which is taken during an overcast day, and a simulated render of the model are shown in Figure 6.

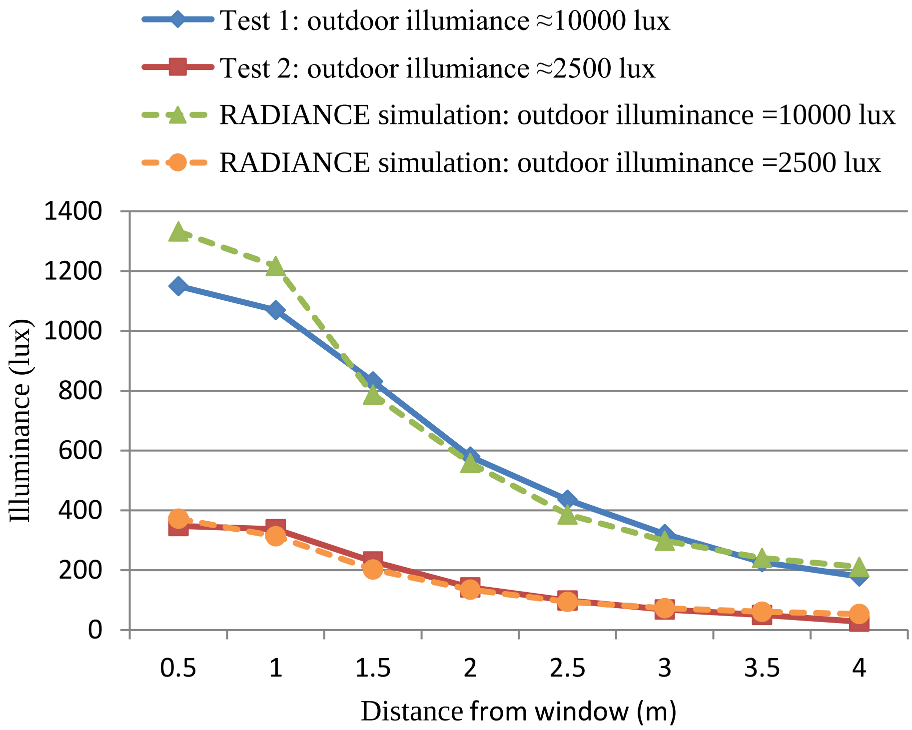


Figure 5: Comparison between measured illuminance and illuminance calculated using Radiance at the selected 8 points in the room

(a) (b)

Figure 1: (a) Photo of test room and (b) rendered image

4. Results and discussion of the effect of different PS-TIM on indoor daylight performance

The criterion for identifying the optimised PS-TIM configuration was based on attaining a balance between the daylight availability and daylight comfort level.

4.1 The effects of slat pitch on daylight performance

Simulations were undertaken for the PS-TIM with Lambertian diffuse translucent slats placed horizontally between two glazing panes, at various slat pitch of 15 mm, 10 mm, 7.5 mm and 5 mm, (labelled as ‘15 mm PS-TIM’, ‘10 mm PS-TIM’, ‘7.5 mm PS-TIM’ and ‘5 mm PS-TIM’ respectively in preceding discussions). For the results presented in this section, the office is assumed to be located in London with the window facing south.

The *useful daylight illuminance* (*UDI*) (see Table 1 and 2 for more information) was determined by sorting the simulated hourly illuminance at the points of interest into 3 bins:

1) an *undersupplied* bin (illuminance value < 100 lux);
2) a *useful* bin (100 lux < illuminance value < 2000 lux);
3) an *oversupplied* bin (illuminance value > 2000 lux).

In this study, a more detailed picture of the middle 100 ~ 2000 lux bin is generated by splitting it into two ranges:

1) A *desired* range (500 ~ 2000 lux), where a typical office design illuminance is met and is not exceeded to the point where glare is highly likely [20];
2) A *sub-desired* range (100 ~ 500 lux) where there is an increasing likelihood that occupants will resort to supplementary lighting to meet their illumination needs.

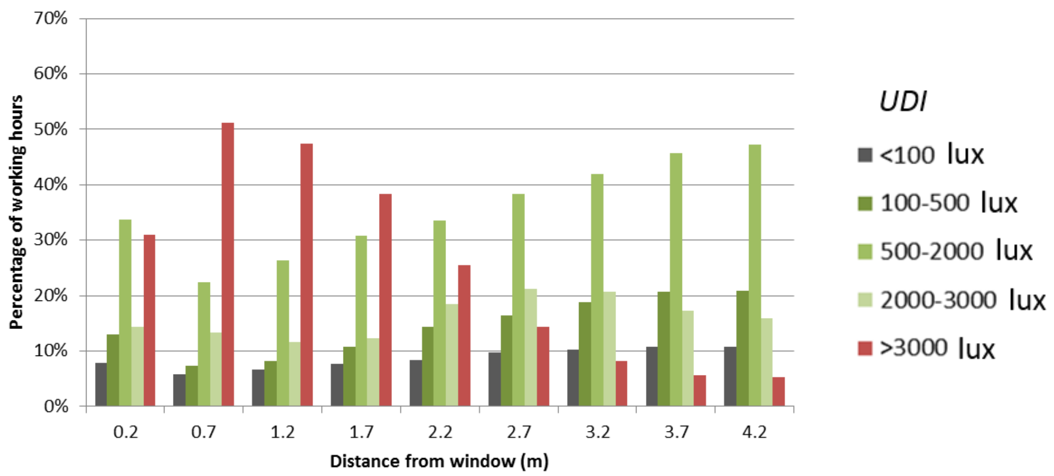
In addition, the oversupplied bin is also divided into two ranges:

1) illuminance in the range of 2000 ~ 3000 lux, in which range occupants may tolerate the strong daylight;
2) illuminance greater than 3000 lux, in which blinds or shades might be lowered [39].

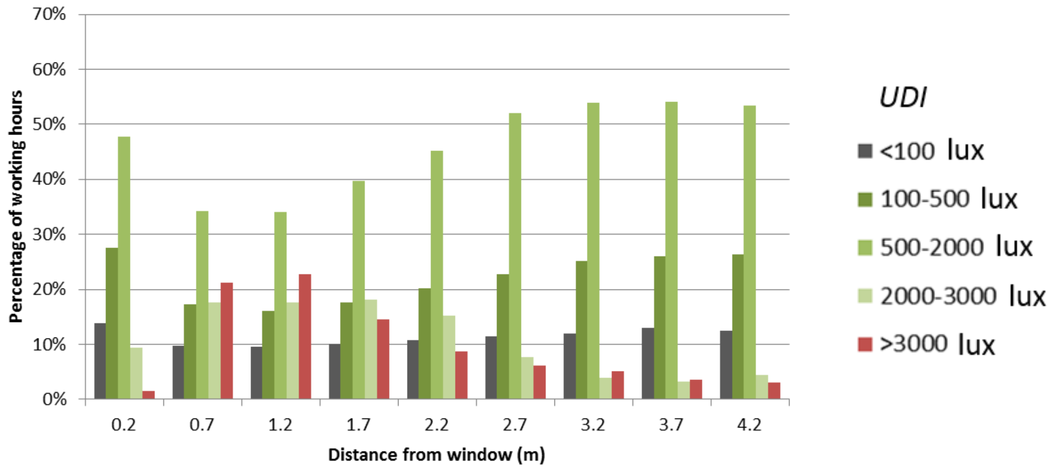
Predictions were made for the window without PS-TIM and with translucent PS-TIM at 4 different slat pitches. Figure 7 shows the *UDI* predicted at points along the centre line of the room between the window and the end wall. As illustrated in Figure 7 (a), for the double glazing system, the period when there is an oversupply of daylight ($UDI_{>3000\ lux}$) accounts for a high proportion (i.e approximately 45% of working hours) at locations within 2.2 m of the window and it gradually reduces to less than 10%, for points further than 3.2 m from the window. This oversupply of daylight can be reduced to less than 20%, 10% 5% and 0% of working hours by integrating PS-TIM structure with slat pitches of 15 mm, 10 mm. 7.5 mm and 5 mm, respectively, as shown in Figure 7 (b), (c), (d) and (e). While the 5 mm PS-TIM can completely eliminate oversupply of daylight, the percentage of undersupplied daylight hours ($UDI_{<\ 100\ lux}$) increases from less than 10% for conventional double glazing to more than 20%. The remaining 3 configurations of PS-TIM give rise to undersupplied daylight hours in the range of 10% to 20% of working hours.

The average percentage of hours where the *UDI* is in the most desired range ($UDI_{500\text{-}2000\ lux}$) increase from 36% for conventional double glazing to 46 % and 50 % when applying PS-TIM with 15 mm slat pitch and 10 mm slat pitch respectively. The integration of PS-TIM improves the daylighting quality of the room, especially within the region that is close to the window where over illumination is frequently a problem with conventional glazing. Instead, more hours are predicted within the most desired range of *UDI* ($UDI_{500\text{-}2000\ lux}$), these being relatively evenly distributed throughout the room depth for PS-TIM with slat pitches of 10mm or less for around 50% of working hours.

Significant improvement over conventional double glazing is achieved by applying PS-TIM with 10 mm slat pitch and 7.5 mm slat pitch, which raises the average percentage of useful *UDI* ($UDI_{100\text{-}500\ lux}$ and $UDI_{500\text{-}2000\ lux}$) from 47% to approximately 76% and 79%, respectively.



(a)



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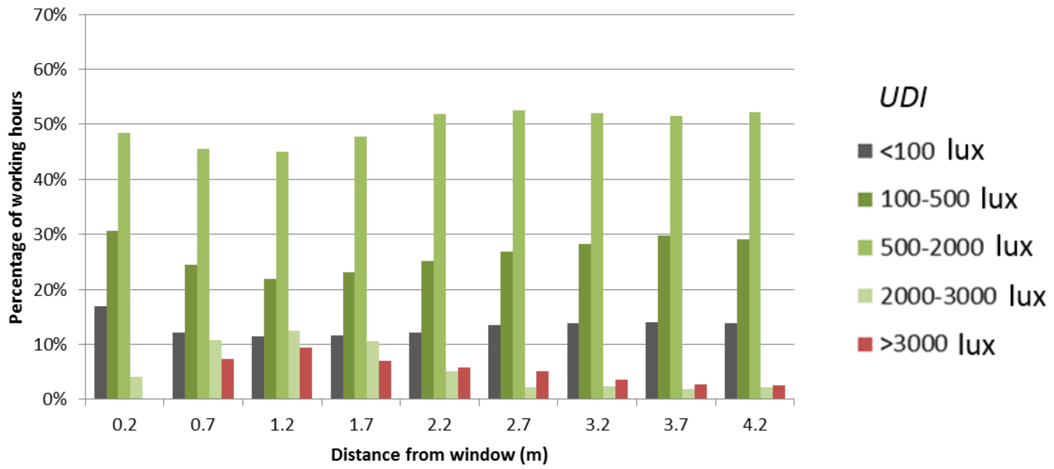

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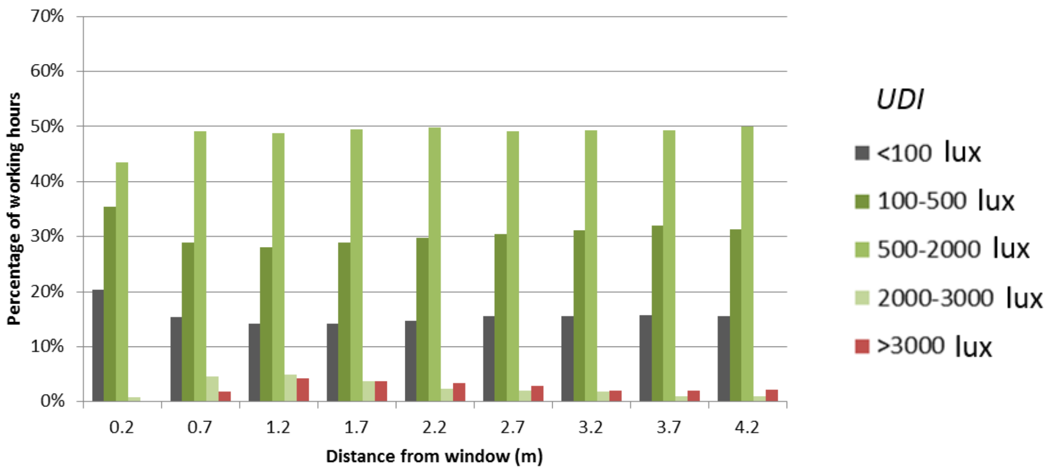

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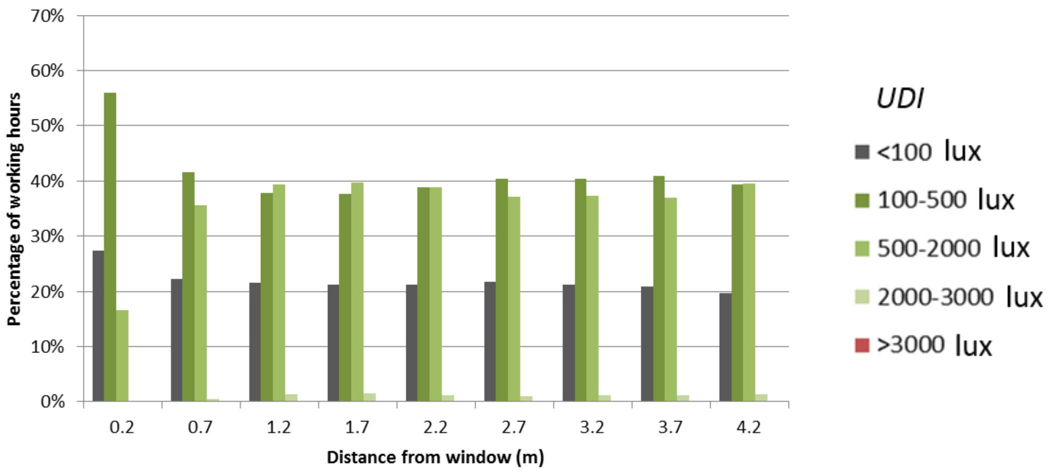


(e)

Figure 7: *UDI* bins for points located along the central line of an office from window to the end wall for the window system with and without PS-TIM: (a) DG; (b) 15 mm PS-TIM; (c) 10 mm PS-TIM; (d) 7.5 mm PS-TIM and (e) 5mm PS-TIM. Simulations are based on a London IWEC weather file.

The results for additional two metrics, *uniformity ratio (UR)* (see Table 1 and 2 for more information) and *daylight glare probability (DGP)* (see Table 1 and 2 for more information), which were used to assess the daylight comfort level are presented in Figure 8.

As with the previous analysis, the data are derived from the London climate data file. At this latitude, 3% of the working hours occur before sunrise or after sunset and so have no daylight at all: for 3% of the time therefore, the *UR* equals 0. For conventional double glazing, the daylight transmitted into the room produces extreme contrasts of illumination on the working plane: 42% of the annual working hours have a *UR* larger than 1:4.5 (labelled as > 4.5 in Figure 8 (a)) and of working hours 47% fall into the range between 1:3.5 and 1:4.5 (labelled as 3.5 - 4.5). The application of PS-TIM integrated double glazing improves the predicted illuminance uniformity. *UR* over 1:2.5 (the sum of the data labelled as 2.5-3.5, 3.5-4.5 and > 4.5), reduces to 34%, 15%, 10% and 4% of annual working hours for PS-TIM with slat pitches of 15mm, 10mm, 7.5mm and 5mm, respectively.

The *daylight glare probability* (*DGP*) is calculated based on a simplified annual simulation method for the assumed occupant position near the window (1.2 m away from window at 1.2 m height) [4, 5]. As shown in Figure 8 (b), for the normal double glazed window, the intolerable glare ($DGP \geq 0.45$), disturbing glare ($0.4 < DGP < 0.45$), and *perceptible* glare ($0.35 < DGP < 0.4$) account for 13.9%, 6.4% and 16.6% of working hours, respectively. When diffuse translucent PS-TIM structures are applied, significant improvement of the percentage of *imperceptible* glare ($DGP \leq 3.5$) is achieved. This increases from 63.1% of working hours for DG to 87.8%, 93.4%, 96.5% and 99.2% with the application of PS-TIM with slat pitches of 15 mm, 10 mm, 7.5 mm and 5 mm, respectively. According to the Wienold's criteria [4] for categorising glare conditions in a room, when 7.5 mm PS-TIM and 5 mm PS-TIM are applied, the room has a '*Best*' classification for over 95% of office working hours and the glare sensation would be deemed *imperceptible*. The 10 mm PS-TIM offers a '*Good*' classification as over 95% of office working hours the glare is *perceptible* and the 15 mm PS-TIM has a '*Reasonable*' classification as fewer than 5% of office working hours have *intolerable* glare.

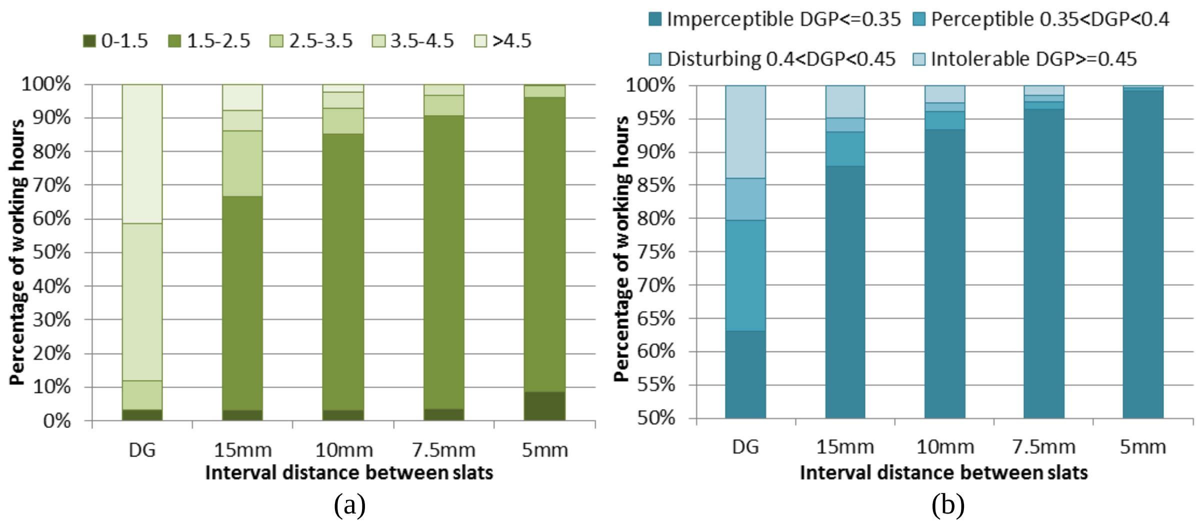
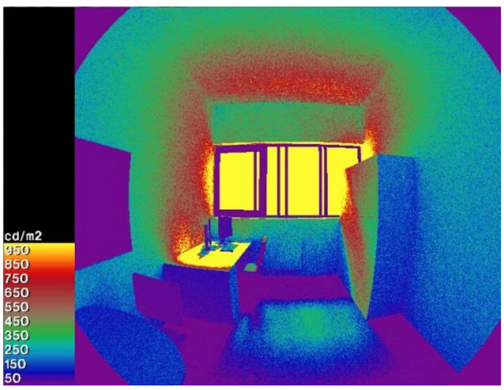
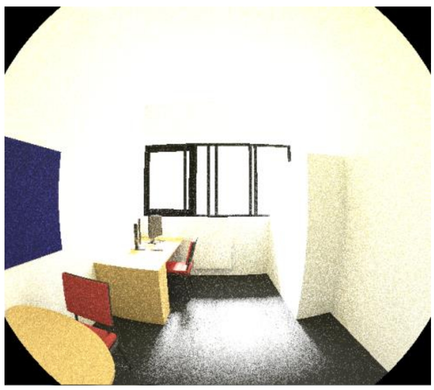


Figure 8: (a) Illuminance *uniformity ratio (UR)* (b) *daylight glare probability* (*DGP*) of window without and with diffuse translucent PS-TIM with 4 different slat pitches

In order to provide a more intuitive impression of the daylight distribution and glare in the office to accompany these metrics, false colour and true colour visualisations for noon on the 21st March were generated and are shown in Figure 9. The presence of PS-TIM results in a more homogenous distribution of daylight and the level of homogeneity increases as the slat pitch gets smaller.

	Equinox (March) 12pm	
DG		

15mm

10mm

7.5mm

5mm

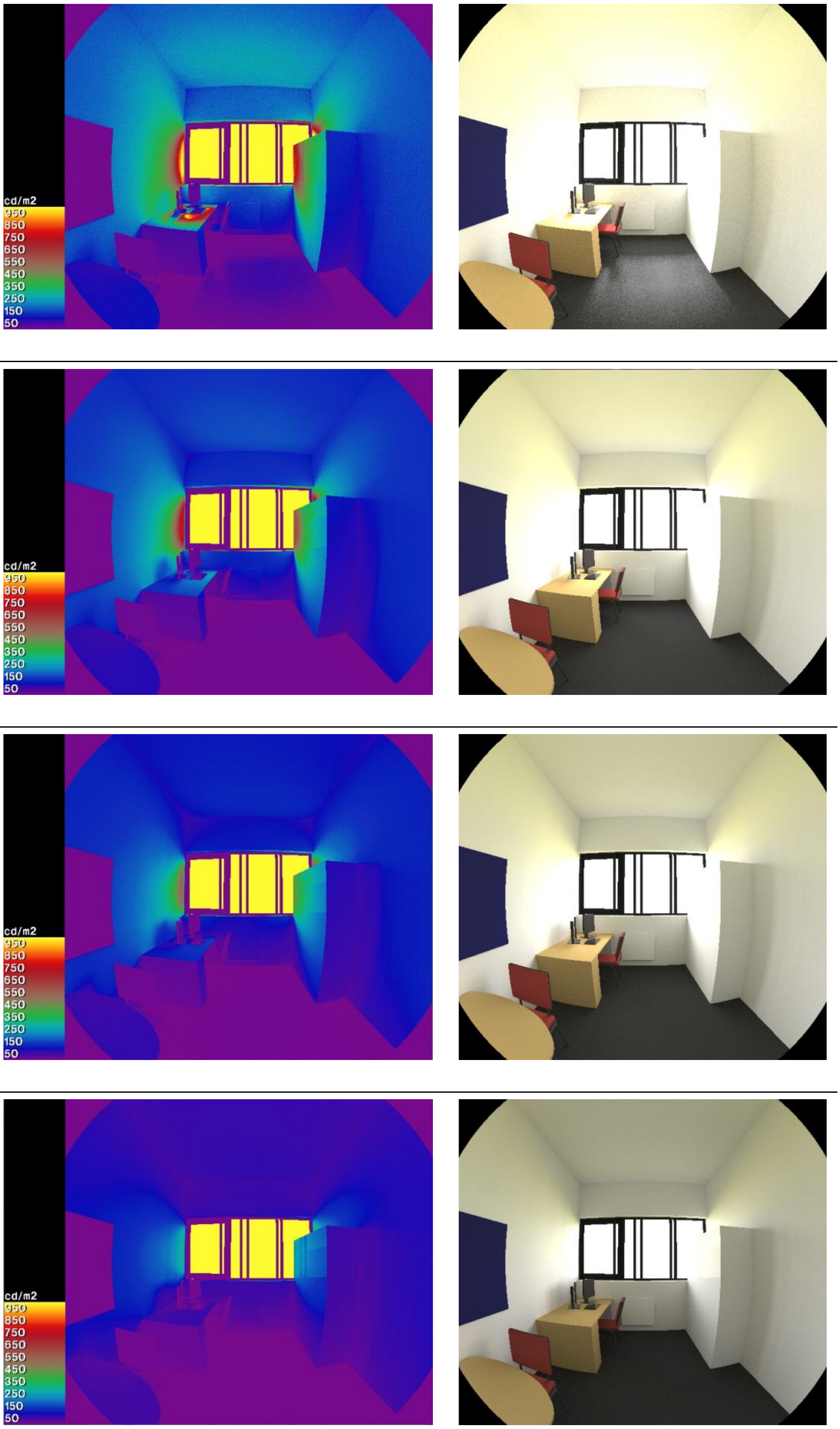


Figure 9: RADIANCE false colour and visualizations and associated *DGP*s for window with and without PS-TIM with different slat pitches for London on 21st March at 12pm under a CIE clear sky.

4.2 The effects of slat tilt angle on daylight performance

In this section, simulation was undertaken for the PS-TIM with Lambertian diffuse translucent slats placed with fixed slat pitch and the slat tilt angles, (ϕ), was varied between -60° and 60°, (labelled as '-60°', '-45°', '-30°', '0°', '30°', '45°' and '60°' respectively in preceding discussions). Figure 10 shows the variation of illuminance *UR* and *DGP* for a 15 mm PS-TIM at different tilt angles. This PS-TIM slat pitch was selected because it is the least effective of the non-tilted configurations studied in section 4.1 (see Figure 10), therefore, further investigations have been carried out to explore whether varying tilt angle has the potential to improve its performance.

It can be seen in Figure 10 (a) and (b), that with the slats tilted at positive angles relative to the sky vault (i.e. ϕ= 30°, 45° and 60°), the performance was worse than that of the PS-TIM with non-tilted slats in terms of both daylight *UR* and *DGP*. Improved performance can be observed in the data for slats with negative tilt angles if *UR* < 3.5 and *DGP* < 0.4 are used as metrics. The percentage of working hours with *UR* below 1:2.5 improves from 66% when slats are horizontally placed to 80% when slats are tilted at -30° and working hours with *DGP* below 0.35 improves from 87% when slats are horizontally placed to around 90% when slats are tilted at angles of -30°, -45°and -60°.

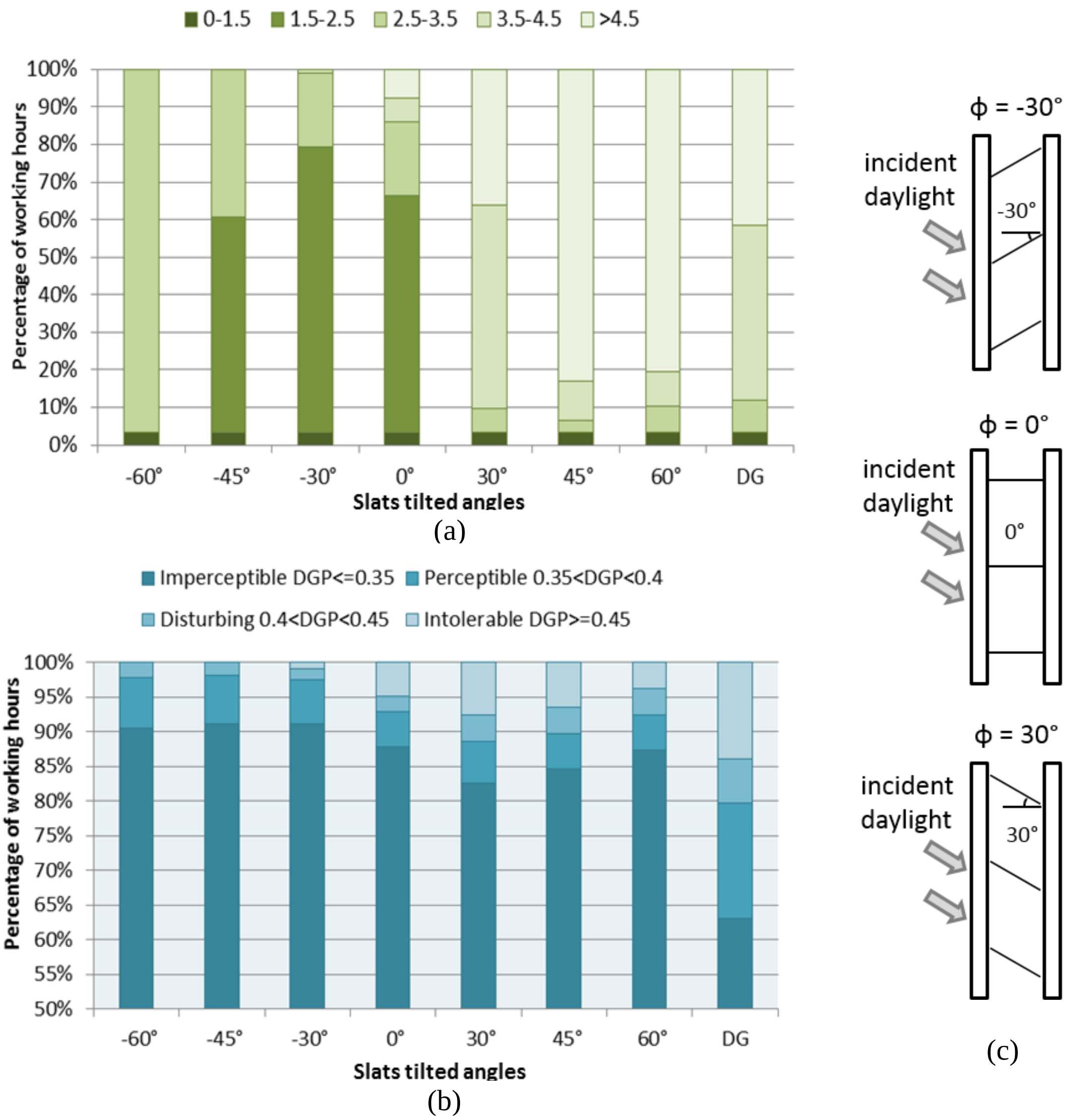


Figure 10: (a) Illuminance *uniformity ratio (UR)*, (b) *daylight glare probability* (*DGP*) for a window with diffuse translucent PS-TIM with slat pitch of 15mm at 7 different tilt angles, and (c) definition of tilt angles, ϕ.

In terms of improving daylight comfort levels, Figure 10 also suggests that only PS-TIM with a tilt angle of -30° offers improved comfort over horizontally placed slats. Section 4.1 indicated that the 7.5 mm PS-TIM was the optimised pitch configuration for improving both daylight availability and daylight comfort. On this basis, the performance of the 7.5 mm PS-TIM with -30° tilted slats and 7.5 mm PS-TIM with non-tilted slats (labelled as 0°) were compared in terms of daylight availability (i.e. $UDI_{100\text{-}2000\ lux}$ and $UDI_{500\text{-}2000\ lux}$) as shown in Figure 11. When evaluating the *UDI* in the range from 100 to 2000 lux, there is no significant difference between the 7.5 mm PS-TIM system with slats tilted at angles of 0° and -30°. For the most desired daylight range of 500 to 2000 lux, the *UDI* values of these two tilt angles are almost the same in the region close to the window (i.e. up to 1.7 m into the room). However, at locations deeper within the room, the *UDI* values for PS-TIM with non-tilted slats remain constant at around 50% of working hours, while those for the -30° tilted slats show a steady decrease with only 30% of working hours indicating a favoured *UDI*. It can be concluded that for the PS-TIM with slat pitch of 7.5 mm, 30° tilted slats do not provide significant improvement of daylight availability when compared with non-tilted slats.

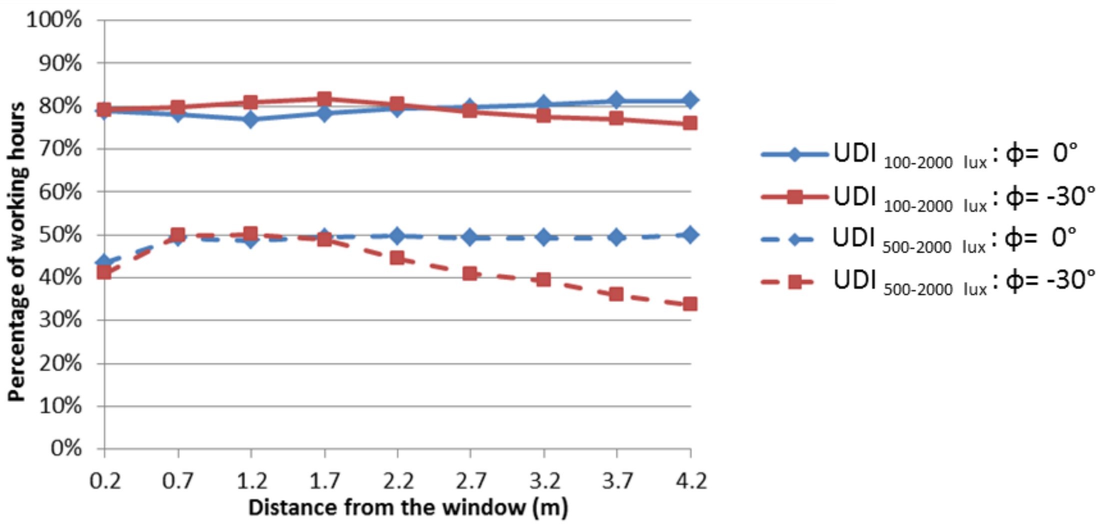


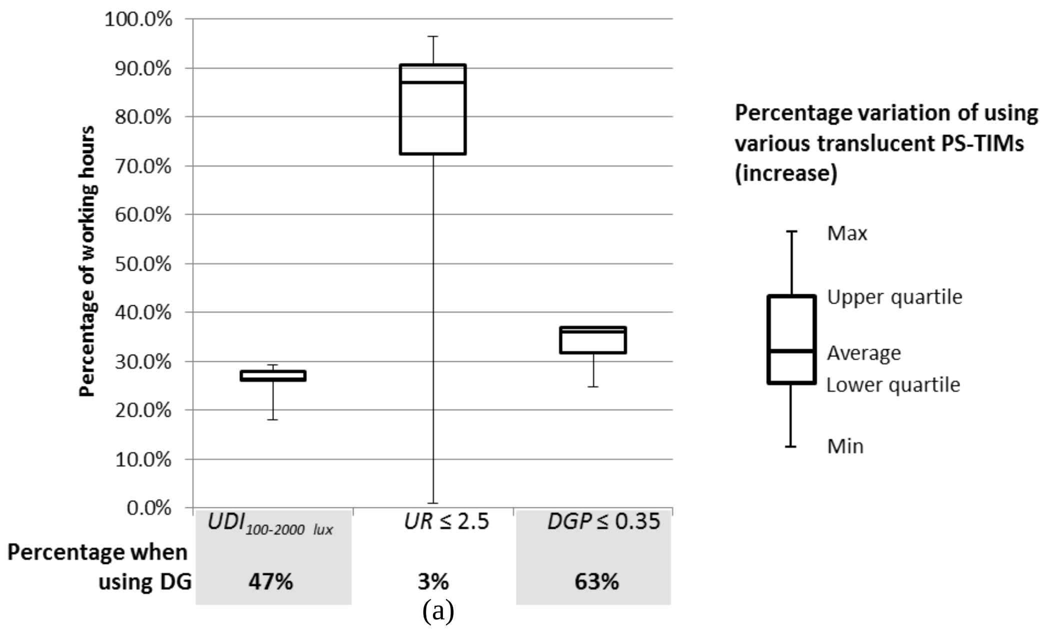
Figure 11: $UDI_{100\text{-}2000\ lux}$ and $UDI_{500\text{-}2000\ lux}$ for diffuse translucent PS-TIM with 7.5 mm slat pitch at 0° and -30° tilt angles

4.3 The effects of slat material properties on daylight performance

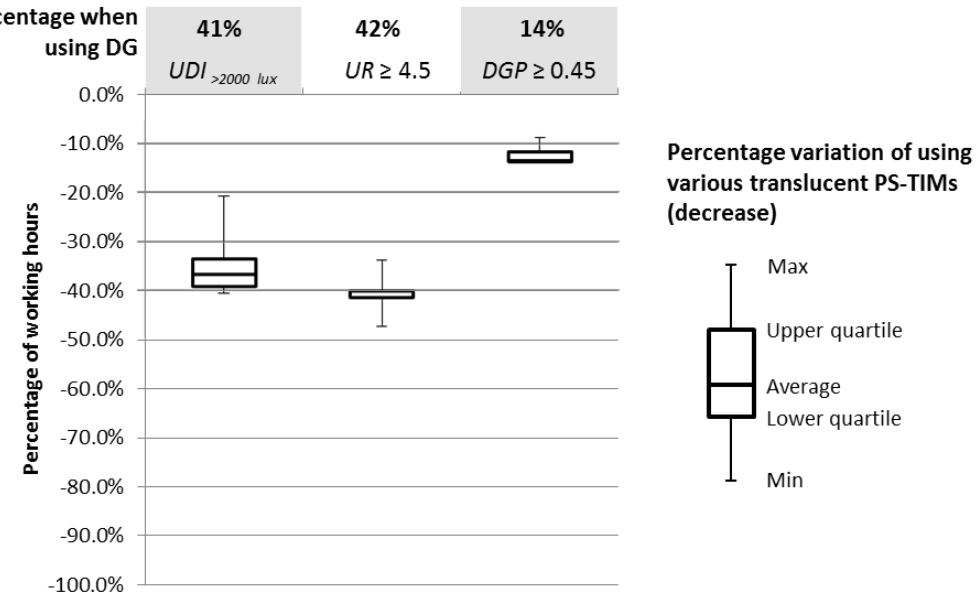
Sections 4.1 and 4.2 discussed the performance of PS-TIM with Lambertian diffuse translucent slats located in the air cavity between the two panes of a double glazing unit. The analysis was performed for various slat pitches (i.e. 15 mm, 10 mm, 7.5 mm and 5 mm) and various tilt angles (i.e. -60°, -45°, -30°, 0°, 30°, 45° and 60°) in a south facing office using the climatic data for London. This section repeats part of this analysis (i.e. *UDI*, *UR* and *DGP*) but replaces the PS-TIM diffusing slats with a transparent material.

The results of using *UDI*, *UR* and *DGP* to evaluate the performance of various configurations of PS-TIMs with Lambertian translucent slats were summarised in Figure 12.

Figure 12 (a) indicates that applying translucent PS-TIMs could increase the percentage of working hours when the metrics lie in their desirable ranges (i.e. *UDI* in *useful* bin, *uniformity* below 2.5 and *DGP* below 0.35) when compared with a standard double glazed window. Figure 12 (b) shows the reduced percentage of working hours when the metrics lie in their undesirable ranges (i.e. *UDI* in *oversupplied* bin, *uniformity* over 4.5 and *DGP* over 0.45) as compared with the data for a standard double glazed window. As can be seen in Figure 12 (a), the percentage of working hours during which the average *UDI* lies in the range of 100-2000 lux, *DGP* ≤ 3.5 and *UR* ≤ 1: 2.5 were 47%, 3% and 63% for standard double glazing unit. These metrics can be increased by between 18 ~ 29% (*UDI*), up to 97% (*UR*) and 25 ~ 37% (*DGP*), respectively, when PS-TIMs are applied. In addition, for the undesired ranges of these metrics, as shown in Figure 12 (b), the percentage of working hours when the average *UDI* is over 2000 lux is 41% for the double glazing unit, and it can be reduced by between 21% and 40%, depending on the type of PS-TIM used. There are 42% of working hours where the *UR* is higher than 1: 4.5 and 14% of working hours where the *DGP* is higher than 0.45 when using a standard double glazing unit: these two undesired situations can be completely eliminated by integrating translucent PS-TIMs.



(a)

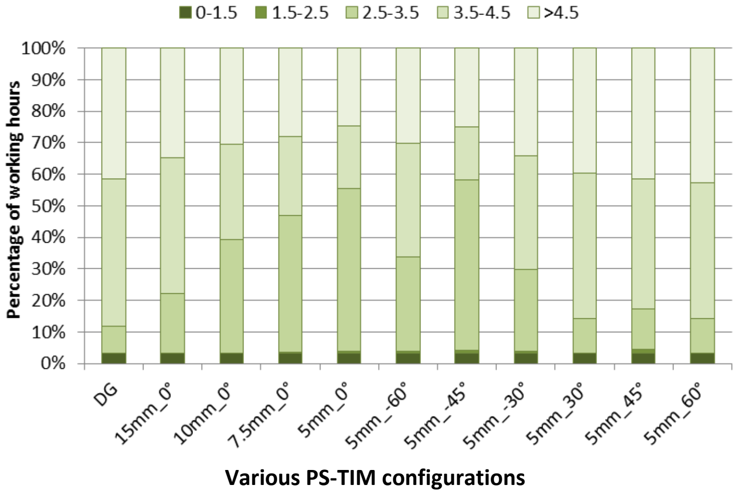


(b)

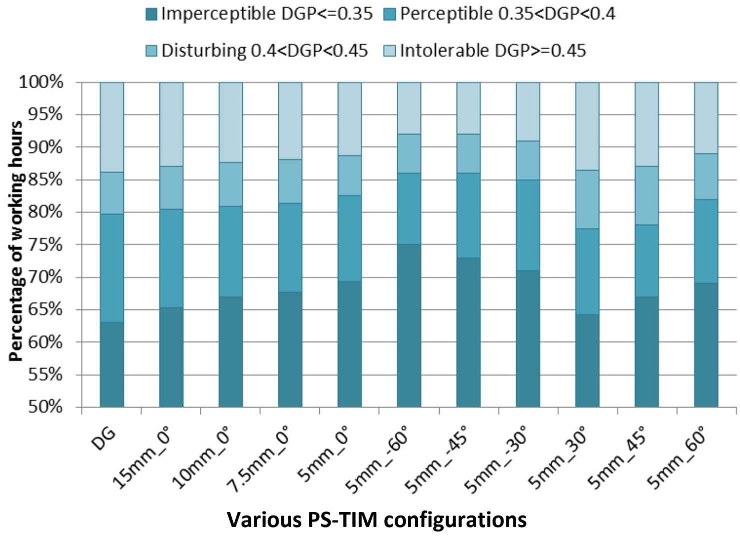
Figure 12: Summary of performance metrics for PS-TIMs with translucent slats in (a) desirable ranges and (b) undesirable ranges.

Figure 13 shows the *UR* and *DGP* after applying various configurations of PS-TIMs with transparent slats, and Table 5 shows the percentage of working hours where the *UDI* is in the range of 100-2000 lux. As can be seen from Table 5 and Figure 13, when comparing PS-TIMs with non-tilted transparent slats to standard double glazing, the 5 mm PS-TIM provides the best performance in terms of reducing the percentage of working hours where the *UR* is over 1: 4.5 (i.e. dropping from 42% to 24%). It also increases the percentage of working hours with *DGP* below 3.5 from 63% to 69%, and slightly improves the percentage of working hours from 50% to 51% where the desirable $UDI_{100\text{-}2000\ lux}$ occurs.

On the basis of these results, the slats with 5 mm pitch were then investigated at various tilt angles (-60°, -45°, -30°, 30°, 45°, and 60°) to identify an optimised configuration. However, the results indicated that there was no obvious improvement in *UR* or *DGP* as compared with the results for the non-tilted slats. Tilt angle has a slight impact on the illuminance distribution. The -60° tilted slats, which have the best overall performance, can improve the $UDI_{100\text{-}2000lux}$ by between 5% - 9% of working hours and improve the *imperceptible DGP* ≤ 3.5 by 11.5% of working hours as compared with the PS-TIM with horizontal slats. However, the window with transparent PS-TIMs does not yield significant improvement in either *UDI* distribution, *UR* or *DGP* as compared with the standard double glazed unit, the results for each being very similar.



(a)



(b)

Figure 13: (a) Illuminance *uniformity ratio (UR)* (b) *daylight glare probability* (*DGP*) for a window with and without transparent PS-TIM for 4 different slat pitches at 7 different tilt angles.

Table 5: ***UDI*$_{100\text{-}2000lux}$ for a window with and without transparent PS-TIM for 4 different slat pitches at 7 different tilt angles.**

	0.2	0.7	1.2	1.7	2.2	2.7	3.2	3.7	4.2
DG	47%	30%	34%	42%	48%	55%	61%	66%	68%
15 mm_0°	48%	31%	36%	42%	48%	55%	60%	65%	67%
10 mm_0°	49%	32%	37%	43%	48%	55%	60%	65%	67%
7.5 mm_0°	50%	33%	38%	43%	48%	55%	60%	65%	67%
5 mm_0°	51%	34%	38%	43%	49%	55%	61%	65%	67%
5 mm_30°	50%	32%	36%	42%	49%	53%	59%	63%	64%
5 mm_45°	46%	32%	37%	42%	50%	56%	63%	67%	69%
5 mm_60°	48%	33%	40%	43%	50%	58%	66%	70%	71%
5 mm_-30°	54%	35%	39%	43%	50%	57%	65%	69%	71%
5 mm_-45°	55%	37%	41%	44%	52%	59%	66%	72%	74%
5 mm_-60°	55%	38%	42%	46%	53%	61%	68%	75%	76%

5. Results and discussion of applying PS-TIM at different climates and for different room orientations

The performance of the PS-TIM window systems is likely to be influenced by the latitude of the site which they are used on and the orientation of the glazing relative to the sun path. In addition, climatic influences that dictate the balance between clear skies with direct sunlight and overcast skies with diffuse light also influence performance.

This section explores the daylight performance obtained from simulating PS-TIM performance using IWEC weather data for five cities viz Stockholm, London, Beijing, Hong Kong and Singapore. These represent different geographical locations and weather/solar conditions. In addition, the daylight performance for the prototype office facing four different orientations (East, West, South and North) located at London (a relatively high latitude site outside the Tropics) and Singapore (located within the Tropics, close to the equator) is also studied. In these studies, the PS-TIM comprises diffused translucent non-tilted slats contained within a double glazing unit. From section 4, slat pitch rather than slat tile angle showed the most significant effect on the daylight performance, therefore, the sole PS-TIM variable explored in this section. As in the previous sections, the *useful daylight illuminance* (*UDI*) was predicted at regular points located along the centre line of the room between the window to the end wall as indicated in Figure 4. The other two metrics, *UR* and *DGP*, were not considered because PS-TIMs with all proposed slat pitches showed significant improvement of daylight performance in these two metrics.

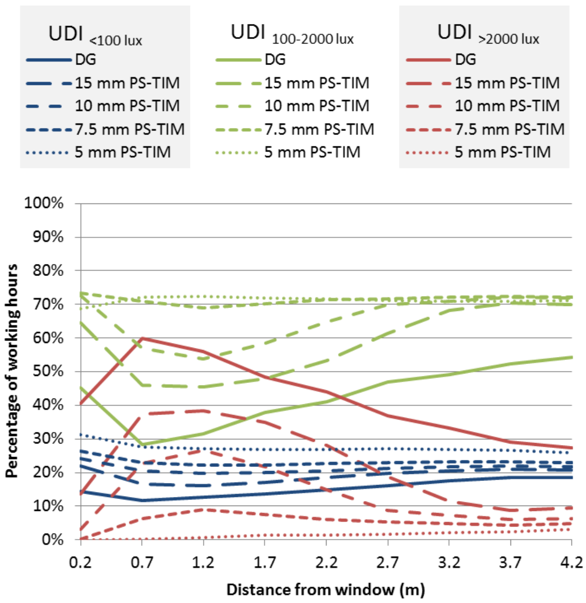
5.1 The application of PS-TIM in different climates

Figure 14 (a) ~ (e) shows the distribution of standard *UDI* bins used to quantify performance for the five different climates considered (these span a latitude range between 1.3 °N for Singapore to 59.3°N for Stockholm). Figure 14 (f) ~ (j) shows data for the modified bin size ($UDI_{500\text{-}2000\ lux}$), which captures only data that meet the design illuminance of at least 500 lux. This provide greater detail than using the $UDI_{100\text{-}2000\ lux}$ bin alone.

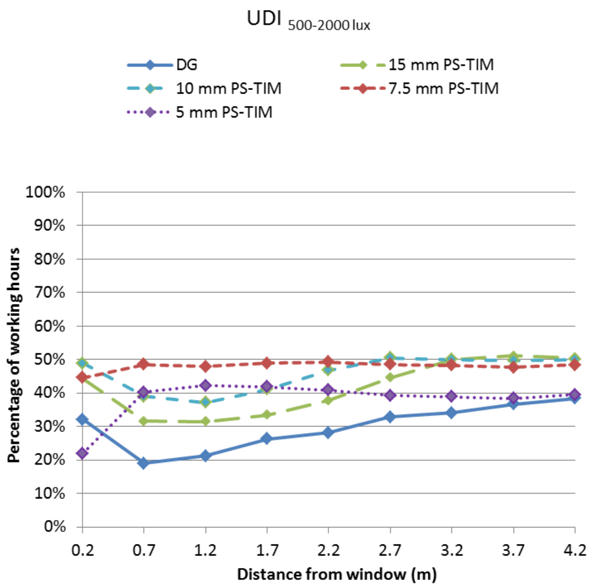
The standard double glazed system shows similar daylight performance for each of the cities considered. In the region close to the window, a significant proportion of the working hours shows *over* illumination (i.e. appearing in the $UDI_{>2000}$ bin). As a consequence, only a small number of hours fall into the *desirable* levels of illumination (i.e. appearing in the $UDI_{500\text{-}2000\ lux}$ bin). The inclusion of PS-TIM improves the luminous environment in the region close to the window by reducing the hours of over illumination and in so doing provides a more uniform illumination of the working plane. As can be seen in Figure 14 (a) and (b), the application of PS-TIMs with 7.5 mm and 5 mm slat pitch can provide relatively even distribution of $UDI_{100\text{-}2000\ lux}$ and improve its proportion to approximately 70% and 80% of working hours in Stockholm and London, respectively. When using the additional criteria $UDI_{500\text{-}2000\ lux}$ (as shown in Figure 14 (f) and (g)), it can be seen that with a decrease the slat pitch from 7.5 mm to 5 mm, the percentage of working hours with illuminance in the most desired range reduced. Thus, PS-TIM with a 7.5 mm slat pitch provides the best all round performance in Stockholm and London. For Beijing, as shown in Figure 14 (c) and (h), the PS-TIM with a 5 mm slat pitch can improve the $UDI_{100\text{-}2000\ lux}$ to around 90% of working hours and achieve a homogenous light distribution. However, when compared with PS-TIM with a 10 mm or 7.5 mm slat pitch, it performs worse in the illuminance range of 500-2000 lux, with a greater proportion of working hours falling in the range of 100-500 lux. The application of PS-TIMs with 7.5 mm and 5 mm slat pitch provide a relatively even distribution of $UDI_{100\text{-}2000\ lux}$ and improve the metric to around 90% of working hours. PS-TIM with a 10 mm slat pitch offer the best performance of $UDI_{500\text{-}2000\ lux}$ in Hong Kong (as shown in Figure 14 (d) and (i)). All but PS-TIM with 15mm slat pitch can improve the illuminance in the range of 100-2000 lux to 90% of working hours in Singapore and PS-TIM with a 10 mm slat pitch performed best in the additional $UDI_{500\text{-}2000\ lux}$ criteria.

Generally, as latitude increases a smaller slat pitch is required to achieve optimised performance and evenly distribute the daylight. For example, the 7.5mm slat pitch PS-TIM can provide relatively even distribution of $UDI_{500\text{-}2000\ lux}$ and $UDI_{100\text{-}2000\ lux}$ when applied in London, and PS-TIM with a 10mm slat pitch can achieve similar effect when used in Singapore. This is a consequence of the relationship between solar altitude and the pass angle for the PS-TIM (i.e. $\tan^{-1}$ (slat pitch / cavity width)). This dictates whether direct solar radiation can reach the working plane in the region close to the window or whether this light is incident on the slat and diffused. It is worth noting that for Beijing, only the PS-TIM with a 5 mm slat pitch can achieve a homogenous distribution of $UDI_{100\text{-}2000\ lux}$. This is because the direct solar irradiation is strong in the year of IWEC weather data (as shown in Appendix A) and leads to significant numbers of hours of over supply (i.e. $UDI_{>\ 2000lux}$) despite undergoing attenuation in the diffusing PS-TIM.

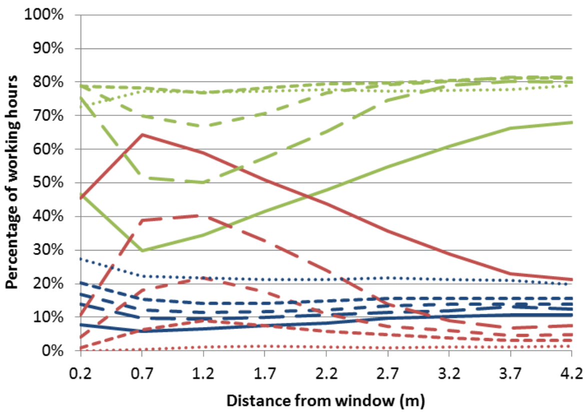
To conclude, both the solar irradiation intensity and the solar altitude angle affect the process of selecting an optimal slat pitch for a window integrating with PS-TIM.



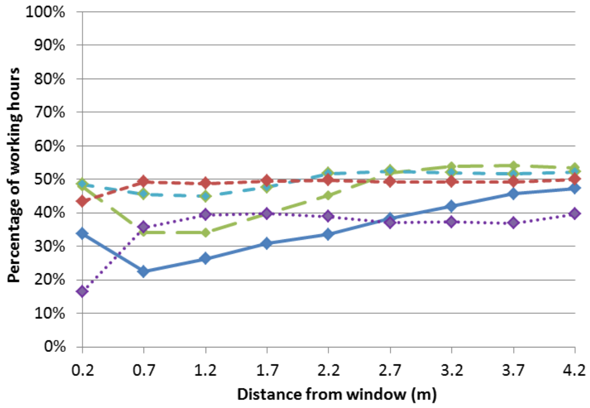
(a) Stockholm *UDI* bins



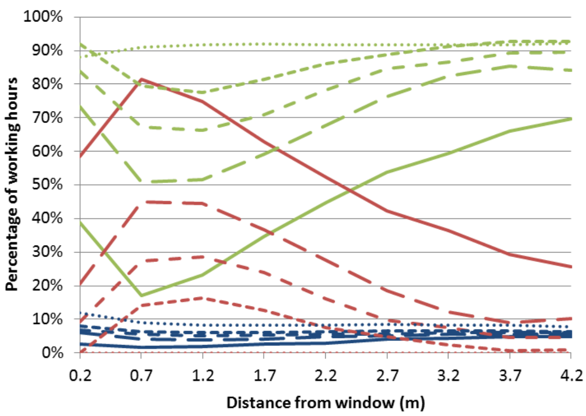
(f) Stockholm $UDI_{500\text{-}2000lux}$



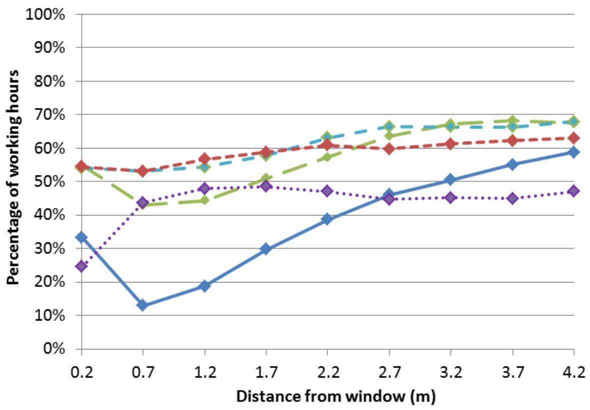
(b) London *UDI* bins



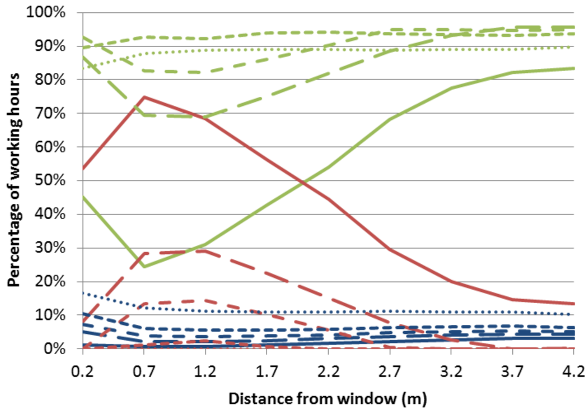
(g) London $UDI_{500\text{-}2000lux}$



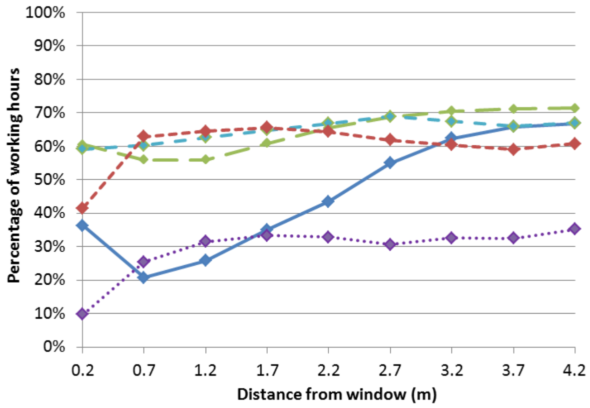
(c) Beijing *UDI* bins



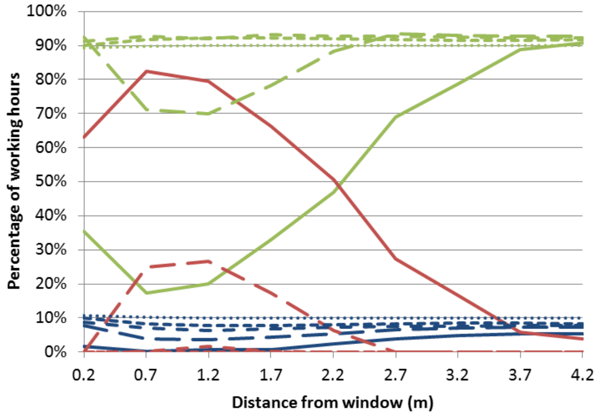
(h) Beijing $UDI_{500\text{-}2000lux}$



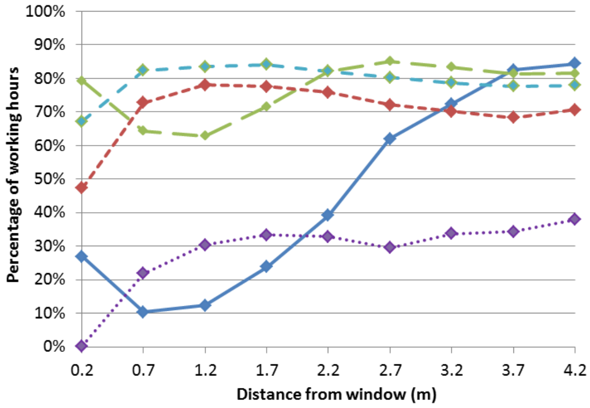
(d) Hong Kong *UDI* bins



(i) Hong Kong $UDI_{500\text{-}2000lux}$



(e) Singapore *UDI* bins



(j) Singapore $UDI_{500\text{-}2000lux}$

Figure 14: (a-e) standard three *UDI* bins and (f-j) $UDI_{500\text{-}2000\ lux}$ bin at points along central line from south-facing window to end wall with and without PS-TIM with 4 different slat pitches under 5 different climate conditions: (a) and (f) Stockholm, (b) and (g) London, (c) and (h) Beijing, (d) and (i) Hong Kong, and (e) and (j) Singapore,

5.2 The application of PS-TIM to windows with differing orientation

The studies thus far in this paper have focused on equator facing facades. These are subject to highest altitude direct solar irradiation in the sun path. This section explores glazing positioned in east and west facades, where lower altitude morning and evening sun predominates, as well as north facing facades, where for the sites chosen in this study, diffuse light tends to dominate.

In this section, only the useful bin (100 ~ 2000 lux) of common three bins *UDI* metric is explored to provide an approximate picture of daylight performance. For a south facing window in London, as shown in Figure 15 (a), the 7.5 mm PS-TIM provides an even distribution and the highest percentage of operating hours (80%) with a useful $UDI_{100\text{-}2000\ lux}$. The north-facing façade mainly receives diffuse skylight rather than direct sunlight, thus, as shown in Figure 15 (b), PS-TIM with any slat pitch can provide a homogenous distribution of $UDI_{100\text{-}2000\ lux}$ with the 15 mm slat pitch providing the highest percentage of $UDI_{100\text{-}2000\ lux}$ being met. For the east and west orientation, the direct solar radiation is incident on the façade at low altitude angles for a short period after sunrise or before sunset and the radiation is not generally as strong as radiation incident on the south façade at noon. Under these conditons, 10 mm PS-TIM is sufficient to achieve a homogenous distribution of light and the highest level of $UDI_{100\text{-}2000\ lux}$ (Figure 15 (c) and (d)). Summarising, for cities with relatively high latitude (e.g. London), the south facing façade requires the smallest PS-TIM slat pitch to maximise useful daylight levels and distribution. Larger slat pitches can be used on the east and west facing façades, while the north facing façade can achieve comfortable daylight using the PS-TIM with largest slat pitch (in this case the 15 mm slat pitch).

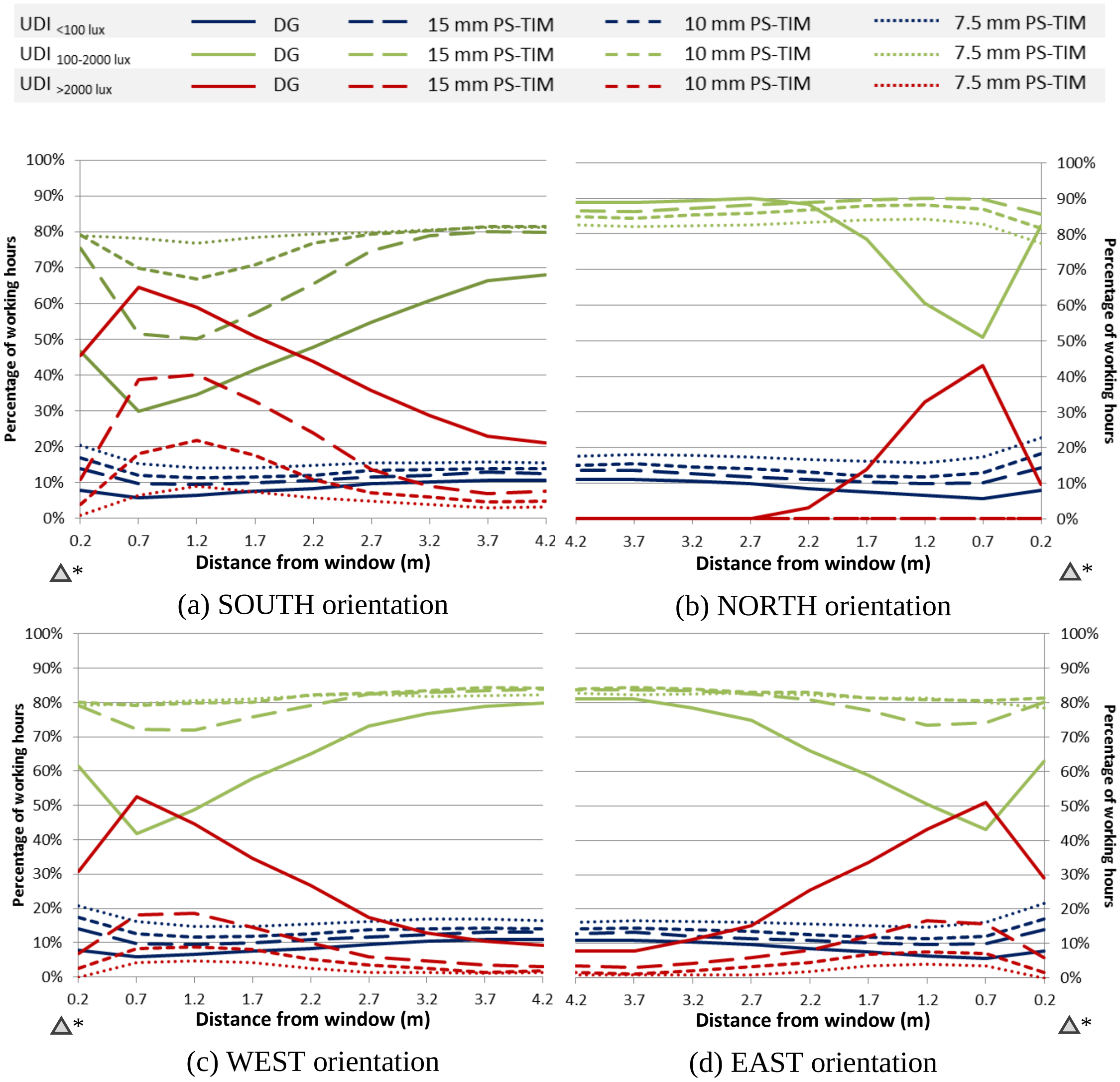
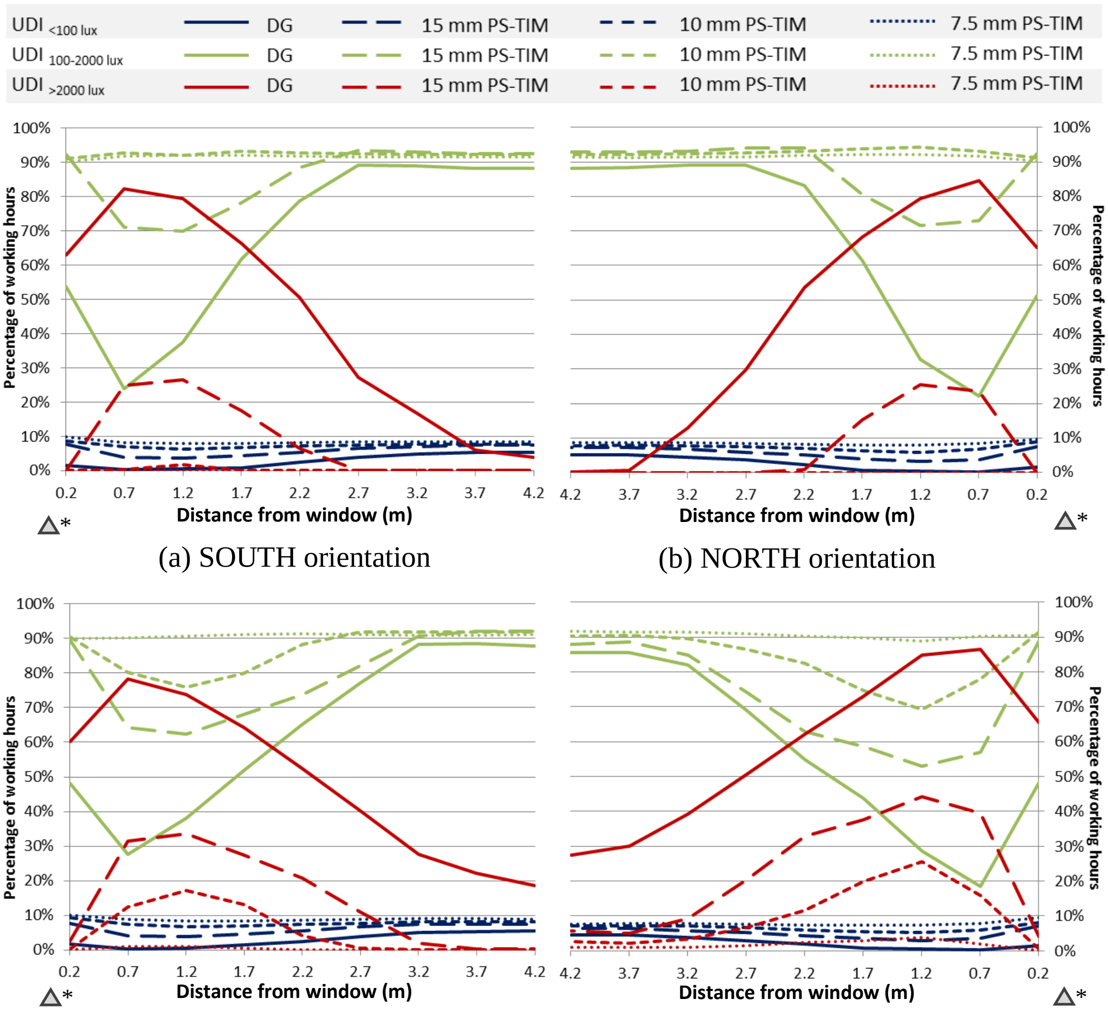


Figure 15: *UDI* bins for points along central line from window to end wall with (a) south, (b) north, (c) west, and (d) east window orientations with and without PS-TIM with 3 different slat pitches under London climate condition.

Singapore (see Figure 16), lies in the Tropics near the equator. As a consequence, the noon solar altitude is high (i.e. over 65°) all over the year and the sunlight is incident on the north and south facades depending on the season. Similar to the conditions in London, the sunlight with relatively low solar altitude is incident on east and west facades in the early morning and late afternoon respectively and has the potential to penetrate deeper into rooms, often with high irradiation levels. Thus, compared with south and north facing façades, where PS-TIM with a 10mm slat pitch is sufficient to deliver a homogenous distribution of $UDI_{100\text{-}2000\ lux}$, the east and west facing façades require PS-TIM with 7.5 mm slat pitch to achieve similar effect. It can be concluded that, for cities with relatively low latitude (e.g. Singapore),

* : Window position

PS-TIM applied to east and west facing façades, requires smaller slat pitches than PS-TIMs applied to south and north facing façades.



(a) SOUTH orientation (b) NORTH orientation

(c) WEST orientation (d) EAST orientation

Figure 16: *UDI* bins at points along central line from window to end wall with (a) south, (b) north, (c) west, and (d) east window orientations with and without PS-TIM with 3 different slat pitches under Singapore climate condition.

* : Window position

6. Conclusion

An investigation of the daylight performance of a double glazed window with integrated parallel slat transparent insulation materials PS-TIMs, for a range of different sites and window orientations was conducted using RADIANCE in combination with *Bidirectional Scattering Distribution Functions* (*BSDFs*) to represent the PS-TIMs' optical performance. The following conclusions can be drawn:

1) PS-TIMs with translucent slats offer better performance than PS-TIMs with transparent slats in terms of *Useful Daylight Illuminance* (*UDI*), *uniformity ratio (UR)* and *Daylight Glare Probability* (*DGP*);
2) when compared with standard double glazing, glazing with integrated PS-TIM can increase the percentage of working hours when the *UDI* lies in the range of 100-2000 lux by between 47% and 79% depending on the type of the PS-TIM used, achieve a homogenous distribution of daylight, and effectively reduce the risk of glare;
3) the use of PS-TIMs at different latitudes suggested that with increasing latitude, a smaller slat pitch is required to maximise useful daylight ($UDI_{100\text{-}2000lux}$) and evenly distribute the daylight. The intensity of solar radiation and the balance of time where clear or overcast skies prevail affect the process of identifying an optimal PS-TIM configuration. While some observations are made, the relationships are not quantified in this study;
4) when applying PS-TIMs to windows with different orientations a general observation for sites located outside of the Tropics is that the smallest slat pitch is required on the equator facing façade, east/west facades provide daylight with a slightly larger pitches and facades facing away from the equator can operate effectively with the largest slat pitch. For sites within the Tropics, north and south facades receive direct irradiation and the slat pitch required is likely to reflect the relative exposure of the two facades ranging from equal on

the equator to relatively smaller pitches on the equator facing façade as you move away from the equator.

This study has restricted itself to exploring the effect of PS-TIM on indoor daylight level. Their influence on the overall energy performance will be presented in further research papers.

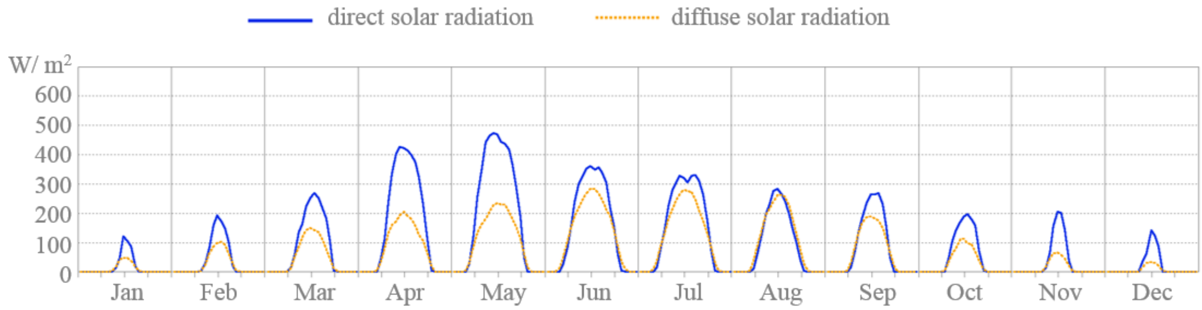
The effects that PS-TIM has on the view into and out of a building are not considered in this study. As part of an overarching glazing strategy, PS-TIM may therefore be usefully used to maintain the external appearance of a glazed façade and admit daylight above and below any regions of a façade reserved for maintaining view out of or into a building, where conventional glazing would be more appropriate.

Acknowledgements

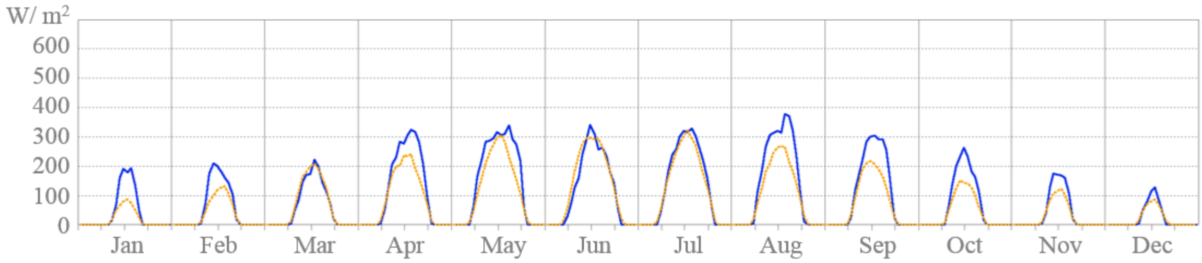
This work was supported by the Faculty of Engineering, University of Nottingham and the China Scholarship Council through a joint PhD studentship awarded to Yanyi Sun.

Appendix A:

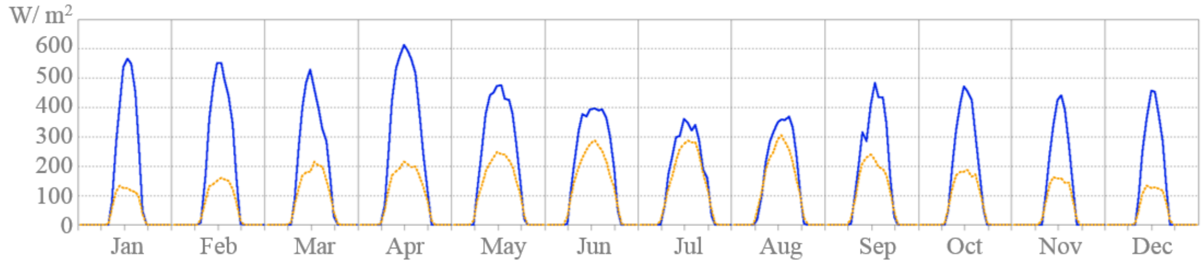
The diurnal average direct and diffuse solar radiation of (a) Stockholm, (b) London, (c) Beijing, (d) Hong Kong and (e) Singapore



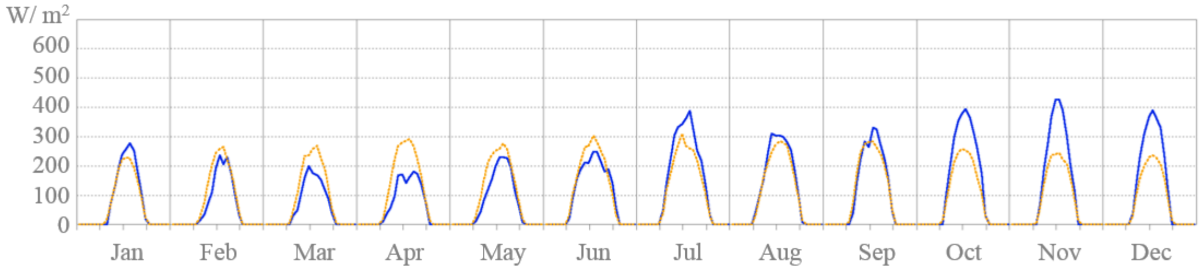
(a) More direct solar radiation than diffuse solar radiation in Stockholm's climate



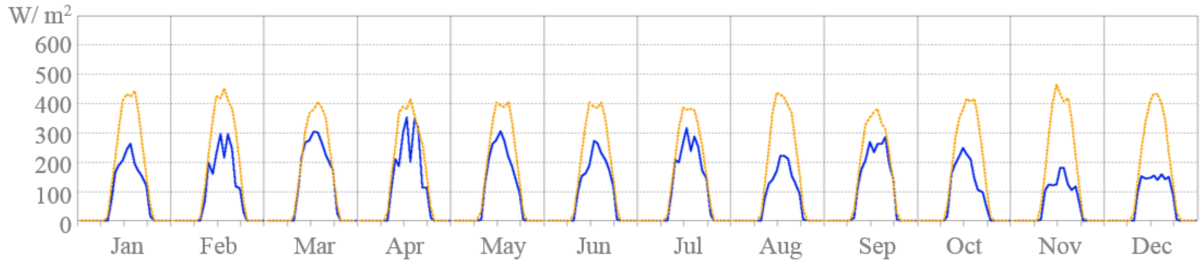
(b) Approximately equal direct and diffuse solar radiation in London's climate



(c) Very strong direct solar radiation in winter, skies diffuse in summer in Beijing's climate



(d) Approximately equal direct and diffuse solar radiation in Hong Kong's climate



(e) Diffuse solar radiation greater than direct throughout the year in Singapore's climate

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