Glazing systems with Parallel Slats Transparent Insulation Material (PS-TIM): Evaluation of building energy and daylight performance

Yanyi Sun, Runqi Liang, Yupeng Wu*, Robin Wilson and Peter Rutherford

Department of Architecture and Built Environment, Faculty of Engineering, The University of Nottingham, University Park, Nottingham, NG7 2RD, UK

*Corresponding author: Tel: +44 (0) 115 74 84011; emails: Yupeng.Wu@nottingham.ac.uk, Jackwuyp@googlemail.com

Abstract

Being responsible for a significant proportion of total heat loss in façade dominated buildings, the design and specification of the envelope, particularly the building's glazing system, is a key factor in determining overall energy consumption. To address this, an innovative double glazed façade system comprising parallel transparent / translucent plastic slats sandwiched between the glass panes to form a Parallel Slat Transparent Insulation Material (PS-TIM) system is proposed as a potential solution. This PS-TIM system reduces heat transfer between the glazing panes whilst maintaining access to solar radiation and daylight.

The presence of the PS-TIM structure significantly affects the thermal and optical performance of the window system in which it is employed. This presents a further significant challenge when trying to predict its performance using dynamic building simulation approaches. Using a typical small office as a case study subject to varying climatic conditions, we investigate the thermal and optical behaviour of a range of PS-TIMs with respect to their daylight and energy performance. We find that when compared to a conventional double glazed system, the application of PS-TIMs can result in a more visually comfortable and uniformly lit environment, which might be desired in an office space, and, in the specific case of the small office under test, can result in a reduction in energy consumption of up to 35.8%. Furthermore, having explored the performance of the system in response to varying climatic conditions, we also present some advice as to how architects and engineers might apply PS-TIMs to window systems or glazed façades.

Keywords:

Parallel Slat Transparent Insulation Materials (PS-TIM); Building simulation; EnergyPlus; RADIANCE.

1. Introduction

Amongst the numerous components that form a façade, glazing systems contribute significantly not only to solar heat gain and heat loss from a building's enclosure, but also determine view, daylight distribution and daylight availability [1-4]. As such, they are exceptionally important elements that, if designed and specified properly, can reduce energy consumption and improve indoor environmental quality. One potential solution to improve the thermal performance of a glazing system whilst maintaining its solar transmittance and access to daylight is to sandwich a Transparent Insulation Material (TIM) in the form of an array of translucent parallel slats into the air cavity of a double glazed unit (Fig. 1). Known as a Parallel Slat Transparent Insulation Material (PS-TIM) structure [5], it divides the interstitial air cavity into small, horizontal, linear cells. In so doing, the cell walls provide additional viscous resistance to the onset of free convection and interfere with thermal radiation transferred from one pane of the glazing unit to the other, hence increasing the thermal resistance of the glazing system overall [5]. At the same time, the translucent slats incorporated within the PS-TIM glazing system have the potential to effectively adjust the quantity and direction of daylight transmitted through the window which in turn may result in a more comfortable and uniform distribution of daylight into the lit space [6]. As such, a well-designed PS-TIM system will bring benefits in terms of both thermal and daylight performance.

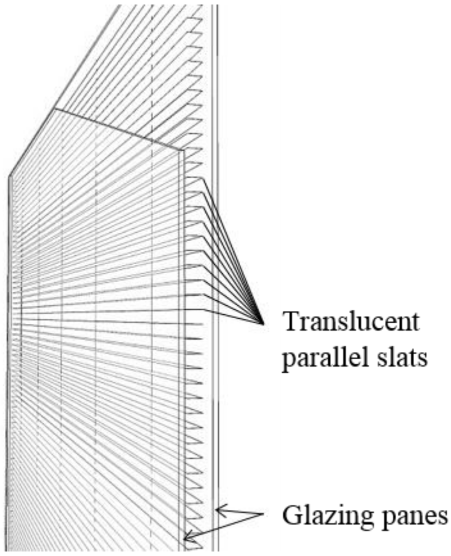


Fig. 1: A schematic diagram of the PS-TIM glazing system

The thermal behaviour of TIMs has been investigated numerically and experimentally over the past two decades, much of this work focused solely on their application to solar collectors. Such research has proven that TIMs can effectively reduce heat loss and improve the overall efficiency of such systems [7-11]. However, relatively few studies exist regarding their thermal and optical performance when sandwiched within the cavities of double glazed window units. This research gap is important as the conditions experienced by a window that incorporates TIMs are significantly different to those in solar collector applications. That is, the working temperature, the pattern and intensity of natural convection within the structure and the requirements for light transmittance and view are dissimilar.

Studying the performance of TIMs within glazing systems presents numerous challenges which remain largely unaddressed in the literature. For example, whilst the thermal resistance of a double glazed unit can be obtained through an empirical equation relating to the Nusselt number, Nu, this is not the case for a TIM structure. In TIM structures, the thermal resistance is dynamic and is a product of environmental conditions affecting both convective and radiative heat transfer within the structure. Primarily driven by both the temperature difference across the glazing panes and the mean temperature of the glazing panes, this changes the structure's total resistance, which in turn affects the overall heat transfer coefficient of the TIM structure [5]. Additionally, detailed analysis of the balance between the thermal resistance and solar transmittance of TIMs and their impact on building energy performance has still not been rigorously explored and few studies have been conducted that seek to analyse their energy efficiency when subjected to varying climate conditions. One study by Wong et al. [12] simulated the performance of TIM-based glazing that incorporated a 22 mm polymethyl methacrylate (PMMA) capillary slab on a south facing façade with a fixed U-value. The annual results for this prediction showed that when compared to standard double glazing, daytime internal temperature swings were reduced and when combined with thermal mass, solar protection and natural ventilation strategies, TIM-based glazing had the potential to reduce heating energy loads in winter and overheating in summer. Finally, whilst daylight and glare studies have been performed for other emerging glazing façade systems such as semi-transparent PV and electrochromic glazing (e.g. [13, 14]), very few have studied the impact of TIMs on daylight performance. One study by Lien et al. [15] used scale model techniques to predict the daylight distribution properties of capillary TIM structures, finding that the capillary TIM structure contributed to uniform daylight distribution and reduced light contrast. However the results obtained from their scale model-based daylight distribution maps do not allow for the reliable prediction of daylight performance of TIM-based glazing under multiple realistic climate scenarios.

It is evident therefore that TIM-based glazing systems require further investigation in terms of both their thermal and optical behaviour, particularly how they shape the daylight and energy performance of the buildings they are applied to. Such information is needed by construction professionals to ensure that TIM-based systems are designed appropriately and applied correctly.

In the paper presented here, we aim to predict the performance of glazing systems incorporating Parallel Slat Transparent Insulation Materials (PS-TIM) by applying them to a small case study office [16] and where appropriate will compare their performance to that of ordinary double glazing. To do so, we present a comprehensive approach to this prediction process that seeks to understand the thermal and optical properties of the PS-TIM based system, these implemented in both building energy and daylight simulation packages (Fig. 2). Using Computational Fluid Dynamics (CFD) simulation, we firstly determine the dynamic thermal conductance of PS-TIM structures in response to varying environmental conditions including the temperature difference between panes and the mean glazing temperature. Using the ray tracing techniques embodied within RADIANCE, we determine the optical characteristics and specifically the Bidirectional Scattering Distribution Function (BSDF) of the PS-TIM structure based on specific geometrical profiles. Having gathered our basic characterisation data, we apply our PS-TIM data to the glazing of a typical small office and test their performance under five different climate scenarios. In so doing, we predict our heating, cooling and lighting demands in EnergyPlus and the daylighting performance of the glazing systems in RADIANCE.

The research presented in this paper will therefore explore glazing performance in increasing levels of detail as it relates to the following research questions:

1. How does PS-TIM slat spacing influence heat losses and gains in PS-TIM systems?

2. How does PS-TIM slat spacing impact on key visual comfort metrics including *Useful Daylight Illuminance* (*UDI*), daylight *Uniformity Ratio (UR)* and *Daylight Glare Probability (DGP)*?

3. What effects do different PS-TIM slat spacings have on heating, cooling and lighting demands and ultimately on overall energy performance?

Overall, the results may be seen as offering potential advice on the design, development and use of PS-TIM windows in buildings subject to these particular conditions.

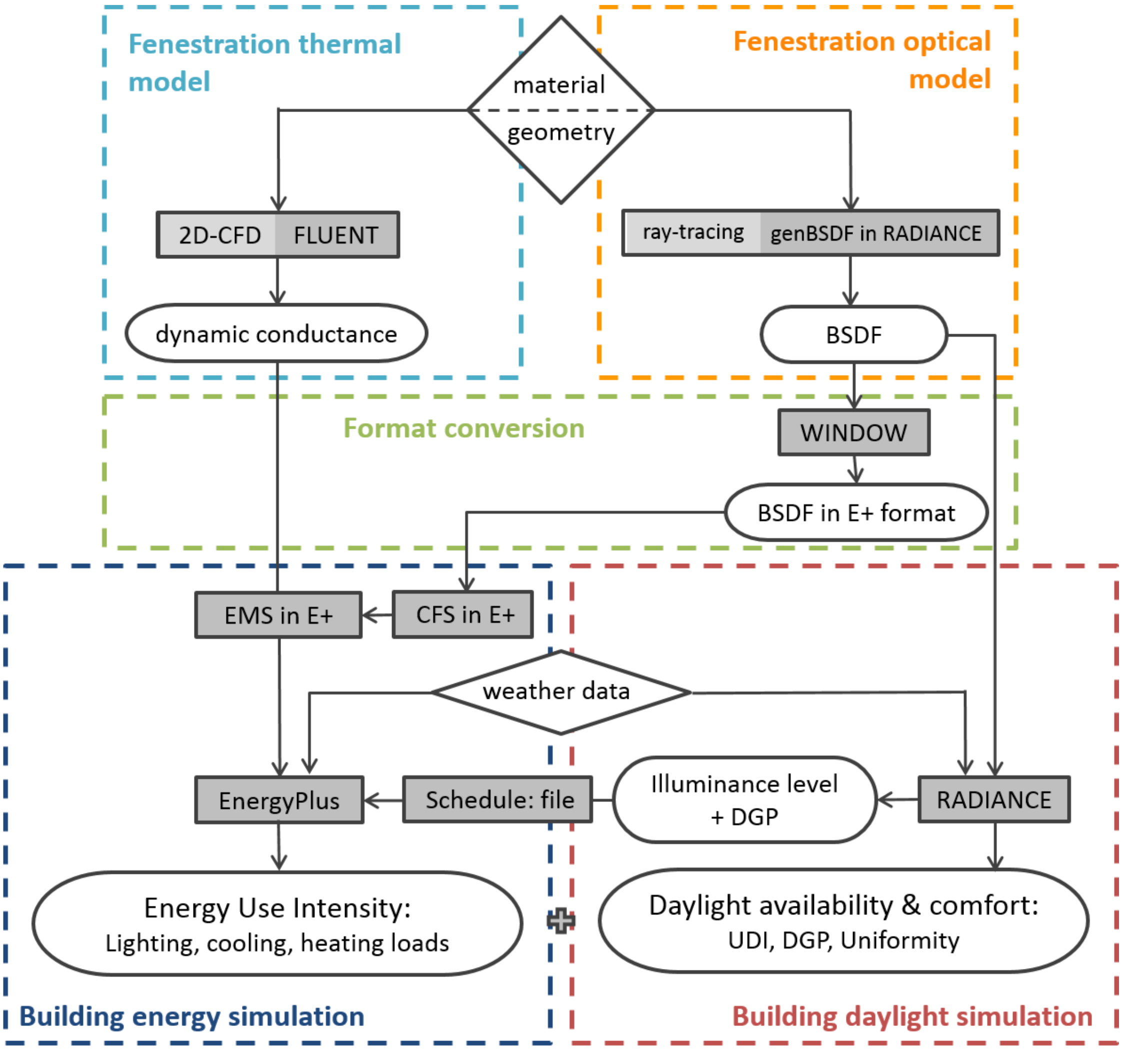


Fig. 2: Flow chart of the comprehensive method for complex fenestration* [17]

*: In this figure, grey rectangles illustrate the algorithm, software or sub-program used in the research, in which E+ is short for EnergyPlus, EMS is short for Energy Management System, CFS is short for Construction: Complex Fenestration State; rounded rectangles illustrate the expected result from the related algorithm, software or sub-program, in which *BSDF* is short for *Bidirectional Scattering Distribution Function*, *DGP* is short for Daylight Glare Probability, *UDI* is short for Useful Daylight Illuminance.

2. Research methodology

In this research, the influence of different climate conditions on daylight and energy performance was explored for three PS-TIM slat spacings. Building upon the authors previous PS-TIM research [5, 6], slat spacings of 10 mm, 7.5 mm and 5 mm (labelled as '10 mm PS-TIM', '7.5 mm PS-TIM' and '5 mm PS-TIM') were selected as they had the potential to significantly increase thermal resistance [5] and improve daylight performance [6] when compared to ordinary double glazing. Since our previous research has demonstrated that slat tilt angle had a nominal influence on overall daylight performance of PS-TIMs for these particular slat spacings [6], the slats were inclined horizontally for the study presented here.

2.1 Base data collection

2.1.1 Thermal model of PS-TIM

To obtain the thermal properties of the glazing system comprising PS-TIMs for use in the resultant building simulation, a validated two-dimensional finite volume model [5, 18] developed using the CFD software ANSYS FLUENT 15.0 was used to solve the conductive, convective and radiative heat transfer properties of the system [5]. In so doing, by varying the boundary conditions in the CFD calculation, an equivalent thermal conductivity under different thermal conditions was obtained for the three slat spacings, these conductivities a function of the mean temperature of the PS-TIM layer and the temperature difference between the two glazing panes. From these CFD calculations [17], Eq. (1) was used to correlate data and the regression coefficients for the fit for the PS-TIM structures with three slat spacings (Table 1).

$$k_{PS-TIM} = a + bt_m + c\Delta t + dt_m\Delta t + e\Delta t^2 + ft_m^2 \tag{1}$$

Where $k_{ps\text{-}TIM}$ is the equivalent thermal conductivity of the PS-TIM, t_m (°C) is the mean temperature of two isothermal interfaces and Δt (°C) is the temperature difference between these two interfaces.

Table 1: Coefficients for the polynomial regression predicting equivalent thermal conductivities of different PS-TIM configurations for Equation (6-5)

	a	**b**	**c**	**d**	**e**	**f**
10 mm PS-TIM	0.0598	$4\text{x}10^{-4}$	$2\ \text{x}10^{-4}$	$-1\text{x}10^{-6}$	$5\ \text{x}10^{-6}$	$2\ \text{x}10^{-7}$
7.5 mm PS-TIM	0.0595	$3\text{x}10^{-4}$	$2\ \text{x}10^{-6}$	$2\ \text{x}10^{-6}$	$3\ \text{x}10^{-6}$	$2\ \text{x}10^{-6}$
5 mm PS-TIM	0.0568	$3\text{x}10^{-4}$	0	0	0	$1\ \text{x}10^{-6}$

From these, a series of individual conductivity values under different thermal conditions were derived for both PS-TIM and ordinary double glazed units (Fig. 3 and Appendix A). These dynamic conductivities were subsequently used in the EnergyPlus simulations.

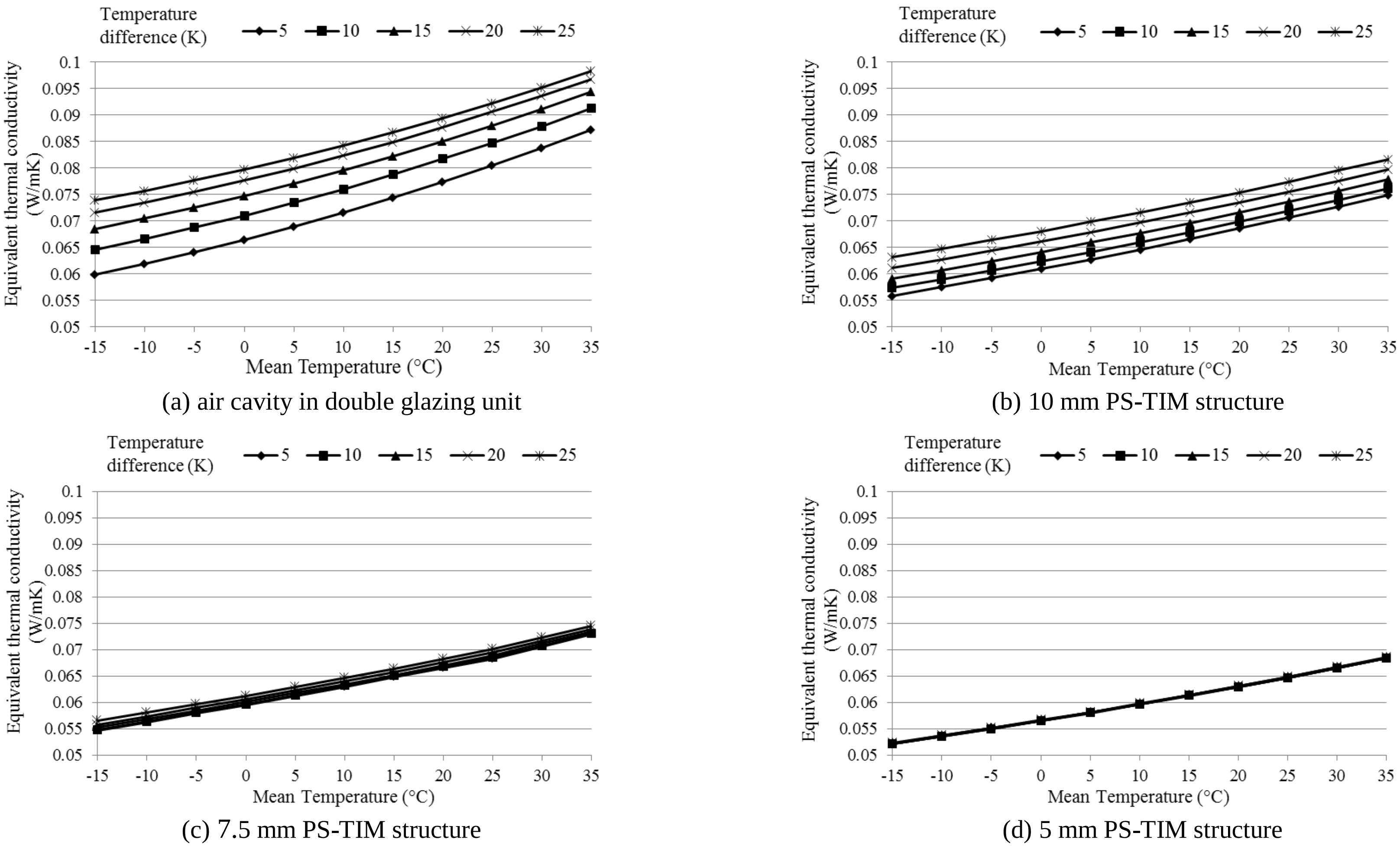


Fig. 3: The equivalent thermal conductivity of the air cavity between two panes with and without PS-TIM, pre-calculated by Computation Fluid Dynamics

2.1.2 Optical model of PS-TIM

To cater for variations in incident angle-related transmission and reflection, a *Bidirectional Scattering Distribution Function* (*BSDF*) was generated for subsequent use in the simulation process. Such an approach for complex glazing systems has been validated and has proven to overcome some of the known limitations of the radiosity method [19-21].

The *BSDF* data were calculated for the three slat spacings (10mm, 7.5mm and 5mm), to reveal the influence of PS-TIM geometry on the daylight and overall energy performance of the office under different climate condition. The material used to form the parallel slats was assumed to be a Lambertian diffuser with 50% transmittance as used by [19]. A validated ray-tracing program in RADIANCE [22], genBSDF, was used to generate the *BSDF* from the geometry and material optical properties of the interstitial structure. The *BSDF* data were subsequently processed in WINDOW 7.4 to create a unified file of the complete system that contained the PS-TIM and glazing layers in EnergyPlus format [19].

2.2 Simulation setup

2.2.1 Weather data in building simulation

The building performance simulations were conducted in one hour time steps for an entire year using the IWEC (International Weather for Energy Calculation) weather data for five cities: Stockholm, London, Beijing, Hong Kong and Singapore. Representing different geographical and weather conditions such as temperature and solar radiation intensity (Tables 2 and 3), these cities were selected to show the different ways in which PS-TIM glazing systems influenced building daylight and energy performance, these explored through both RADIANCE (Version 4.1) and EnergyPlus (Version 8.1.0) simulation.

Table 2: Latitude, longitude, summer and winter average temperatures of the 5 cities

	Latitude	Longitude	Summer avg. temp. (°C)	Winter avg. temp. (°C)
Stockholm	59.3° N	18° E	15.8	-2.0
London	51.5° N	0° W	16.3	4.5
Beijing	39.9° N	116° E	25.4	-1.1
Hong Kong	22.3° N	114.2° E	28.4	16.5
Singapore	1.3° N	103.8° E	Annual avg. 27.4	

Table 3: Monthly average direct and diffuse solar radiation at the 5 cities

	Stockholm		London		Beijing		Hong Kong		Singapore	
	Diffuse (W/m^2)	Direct (W/m^2)	Diffuse (W/m^2)	Direct (W/m^2)	Diffuse (W/m^2)	Direct (W/m^2)	Diffuse (W/m^2)	Direct (W/m^2)	Diffuse (W/m^2)	Direct (W/m^2)
Jan	8.6	15.1	19.0	42.5	38.2	130.9	63.6	71.5	134.1	74.5
Feb	22.7	37.8	32.3	50.9	50.1	145.7	73.3	57.7	142.4	84.6
Mar	45.0	74.3	62.0	54.5	68.3	152.2	79.8	55.6	123.7	96.8
Apr	74.9	157.6	82.5	116.0	79.8	195.4	96.6	56.4	130.5	95.1
May	102.8	197.8	111.5	143.4	95.0	181.4	94.3	72.6	128.8	85.7
Jun	123.7	152.9	123.0	113.7	108.2	163.2	98.8	81.2	126.9	79.6
Jul	120.3	146.2	120.1	129.9	107.2	133.1	100.1	133.8	123.9	92.2
Aug	100.1	99.1	97.2	133.5	104.0	120.0	98.9	106.3	136.7	64.8
Sep	63.1	73.0	72.0	96.1	78.4	139.4	94.2	94.6	119.4	89.9
Oct	30.5	57.7	41.9	73.9	61.6	118.1	83.6	127.5	132.0	69.8
Nov	13.2	32.2	28.6	38.6	46.6	100.1	74.1	114.4	138.8	50.0
Dec	5.9	20.1	17.4	21.9	36.6	102.2	68.7	103.2	130.1	59.3

2.2.2 Modelling of the prototype office

A single room, based on a small office located in the Energy Technologies Building at the University of Nottingham in the UK was selected for the simulation [17]. The purpose of using a single office in building simulation and performance analysis was to use a simple scenario to demonstrate how the PS-TIM integrated into a window system influenced the environment in office buildings in different climates. The office was considered as part of a large south-facing façade with dimensions of 2.9 m (width) × 4.4 m (depth) × 3.3 m (height) (Figure 4), ignoring influences from surrounding buildings, vegetation or other obstructions. Only the south wall of the office was exposed to external conditions while the remaining surfaces were assumed to be buffered by mechanically conditioned spaces and therefore experienced no interzonal heat flow. A window of dimensions 1.4 m (height) × 2.9 m (width) was located in the south wall (see Fig. 4 (b)). The room was assumed to be used as a private office for two people from 09:00 to 17:00 on weekdays, with one seating position near the window and the second at the back of the room.

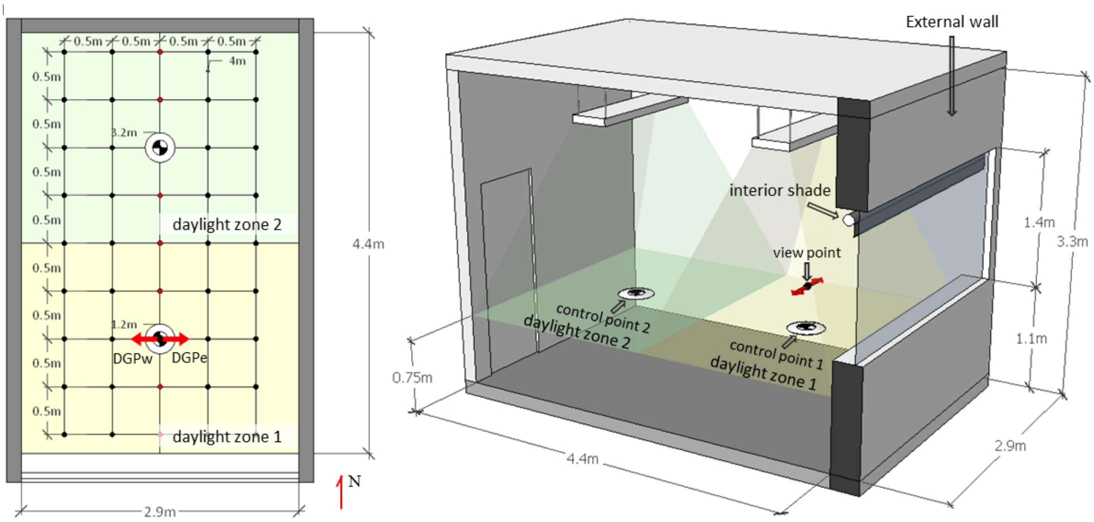


Figure 4: (a) Plan view and (b) section view of the simulated office room

2.2.3 Simulation set up for building daylight prediction in RADIANCE

In this research, the Three-Phase-Method [23], based on hourly weather data, was used for annual dynamic daylight simulation. As shown in

Figure (a), a total of 45 measurement points at a height of 0.75 m above the floor were used to represent the illuminance distribution on a notional work plane. With a cell size of 0.5 m, the resultant illuminance grid met the maximum grid cell size of 0.56 m as calculated from the technique used in [24].

For both occupants, as glare is less likely to be an issue at the back of the room, only the view point representing the occupant working near the window was considered for the glare evaluation. 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, the occupant was considered to be facing away from the window in either an east or west direction (see Fig. 4). A detailed description of the internal reflectance, transmission of the double glazed window and the rendering parameters (e.g. ambient bounces, ambient divisions, ambient resolution etc.) used in RADIANCE can be found in Table 4.

Table 4: Simulation parameters in RADIANCE

Setting for RADIANCE simulation	
Visible reflectance of floor (%)	30
Visible reflectance of wall (%)	80
Visible reflectance of ceiling (%)	80
Visible transmission of double glazed window (%)	78
Ambient bounces [-ab]	12
Ambient divisions [-ad]	50000
Ambient supersamples [-as]	512
Ambient resolution [-ar]	256
Ambient accuracy [-aa]	0.13
Direct sampling	0.2

2.2.4 Simulation set up for building thermal / energy prediction in EnergyPlus

In this research, the U-value of the exterior south wall was assumed to be constant at 0.43 W/m^2K for all five cities, which is a mid-value according to the building regulations for these cities. The dynamic equivalent thermal conductivities derived for both the PS-TIM and double glazing units (Section 2.1.1) were used as input data to the EnergyPlus simulation. By using the ‘Energy Management System (EMS)’ function in EnergyPlus, the internal and external surface temperatures of the tested window were detected at the beginning of each time step. From this, a corresponding thermal conductivity for that temperature condition was selected from the dataset and subsequently applied in the energy balance calculation process [17, 25]. The *BSDF* file derived from the ray-tracing technique (Section 2.1.2) was also used as an input file to EnergyPlus.

Standard equipment and lighting loads were assumed to be 13 W/m^2 and 16 W/m^2 respectively [26, 27]. As shown in Fig. 4, the room was divided into two daylighting zones with two control sensors located at the centre of each daylighting zone at a height of 0.75 m (representing the height of the working place). An illuminance level threshold of 500 lx at each sensor, which is the lower limit for task lighting [28], was used to determine the switching profile of the lighting system with the appropriate sensor individually controlling its own luminaire. To simplify the analysis and negate the influence from variable thermostat setting temperatures on energy consumption under different climate conditions, a single set-point temperature of 21 °C was used all year round. This set-point temperature represented an overlap between summer and winter operative temperature ranges [29]. From this, two HVAC schedule scenarios were applied, these seeking to explore the influence of PS-TIM systems on the office's energy performance during both day and night time. The first assumed that the HVAC system only operated during normal working hours from 09:00 to 17:00 on weekdays. The second assumed that the HVAC system was in operation throughout the year.

Acknowledging the fact that occupants in an office disrupted by bright daylight are likely to lower the interior shade or blind to block sunlight, an assessment of Daylight Glare Probability (DGP) [30, 31] was simulated. Assuming that the occupant faced either the east or west wall from the viewpoint, both the DGP for these orientations (DGPe/ DGPw) and illuminance levels were predicted in RADIANCE. When these DGPs exceeded 0.35, therefore implying the occurrence of perceptible glare [31], and/or illuminance levels exceeded 2000 lx, which implied that daylight was very likely to lead to visual and/or thermal discomfort [28], the interior shade, with a reflectance of 0.5 and a transmittance of 0.1 was lowered. The output data from RADIANCE was subsequently used to generate a daylight schedule for each time step, these forming an input into EnergyPlus. This input determined whether artificial lighting was switched on or not.

3. Simulation results and discussion

3.1 Daylight performance after applying PS-TIM

The BSDF data were used to simulate the daylight performance of the office space as subject to five different climate scenarios through RADIANCE. Key daylight metrics included the daylight availability metric, *Useful Daylight Illuminance (UDI),* and daylight comfort metrics *Daylight Glare Probability (DGP)* and Illuminance *Uniformity Ratio (UR).*

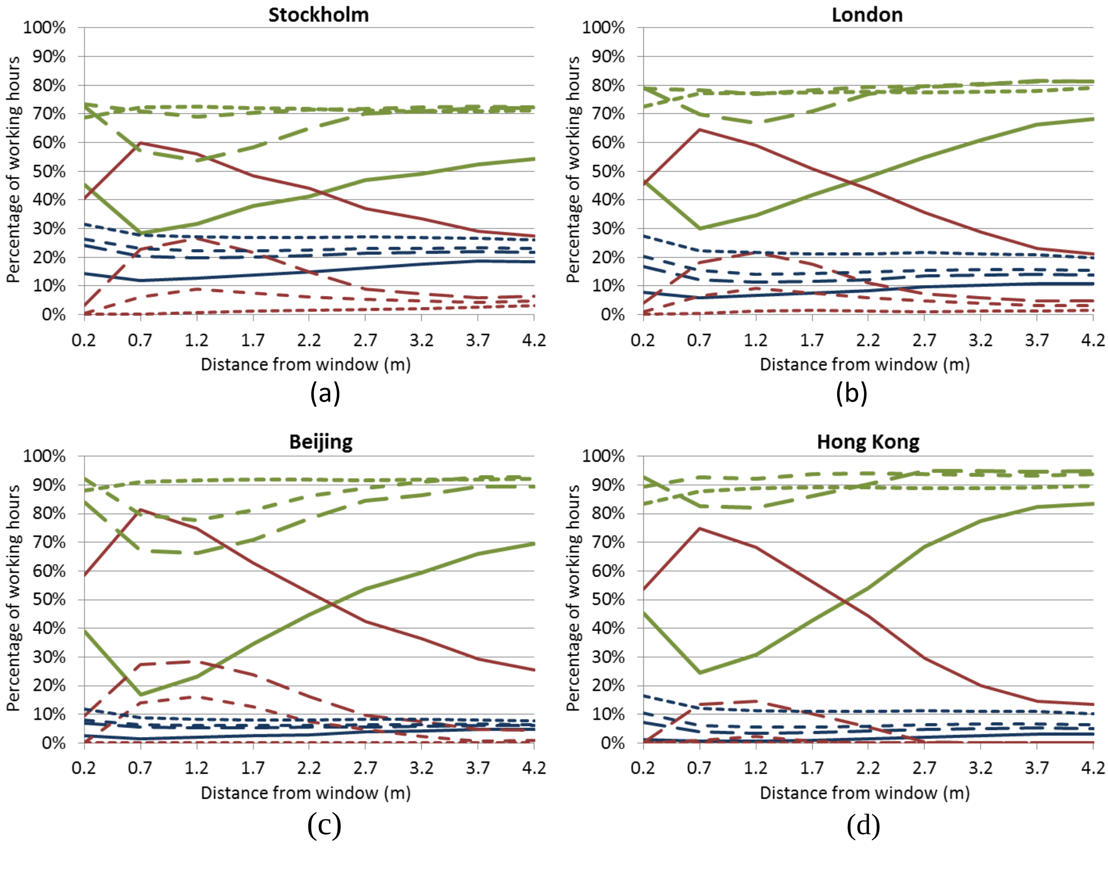
3.1.1 Useful daylight illuminance

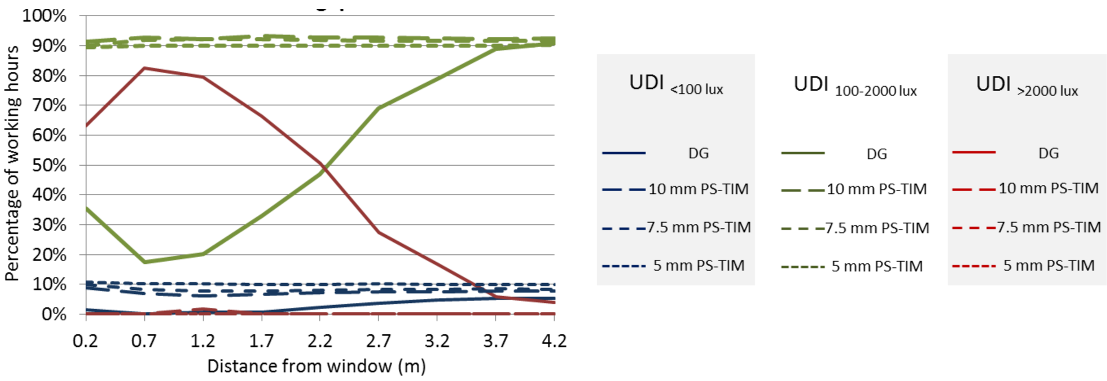
Predicted at points along the centre line of the room between the window and the end wall for the selected five different climatic conditions, the *Useful Daylight Illuminance* (*UDI*) metric was used to explore occupant response to varying daylight illumination [28] for both double glazed and PS-TIM-based units (Fig. 5). In so doing, lower and upper acceptance thresholds describing the illuminance level achieved during the working hours in a year were derived, these categorised into three acceptance threshold bins [28]; (1) an *undersupplied* bin ($UDI_{<100\ lx}$), where the daylight illuminance levels were below 100 lx and insufficient thus requiring supplementary artificial lighting, (2) an *oversupplied* bin ($UDI_{>2000\ lx}$), where the daylight illuminance levels experienced were in excess of 2000 lx and therefore very likely to lead to visual and/or thermal discomfort and, (3) a *useful* bin ($UDI_{100\text{-}2000\ lx}$), which was considered to provide desirable illuminance between 100 and 2000 lx.

Results from the standard double glazed window (Fig. 5) show similar daylight performance under all cities considered. In the region close to the window, a significant proportion of the working hours showed *over* illumination (i.e. appearing in the $UDI_{>2000\ lx}$ bin). The inclusion of PS-TIM systems improved the luminous environment in this region by reducing the hours of over illumination and in so doing resulted in a more uniform illumination of the working plane. As is evident in Fig. 5, for approximately 70% to 80% of working hours in Stockholm and London respectively, of the three PS-TIM spacings, the 7.5 mm and 5 mm slat spacings provided more desirable illumination ($UDI_{100\text{-}2000\ lx}$), this a significant improvement over double glazing. For Beijing (Figure 5 (c)), the PS-TIM with a 5 mm slat spacing improved the $UDI_{100\text{-}2000\ lx}$ to around 90% of working hours, and also demonstrated a significant improvement over double glazing and other PS-TIM spacings, particularly for those regions closer to the window. The PS-TIM with a 7.5 mm slat spacing offered the best $UDI_{100\text{-}2000\ lx}$ performance in Hong Kong (Figure 5 (d)) where both the 5 mm and 7.5 mm slat spacings, demonstrated a more consistent performance across the length of the room. For Singapore, all PS-TIMs provided a relatively even distribution of $UDI_{100\text{-}2000\ lx}$ and improved the metric to around 90% of working hours (Fig. 5 (e)).

Generally, three observations arose from these data. Firstly, all PS-TIM slat spacings outperformed double glazing for all cities. Secondly as latitude increased, smaller slat spacings provided a more even distribution desirable illumination across the length of the office as evidenced by the smaller hourly variation and overall in the percentage of working hours. Thirdly, for those cities other than Singapore, the 10 mm slat spacing gave the poorest daylight performance of all slat spacings for those areas closest to the window and in consequence gave the highest number of working hours that were over illuminated ($UDI_{>2000\ lx}$). Performance however tended to converge with other slat spacings deeper into the room where the lit environment became more diffuse, generally at around 2.7 m. With respect to these final two observations, this results from the relationship between solar altitude and the pass angle for the PS-TIM (i.e. $\tan^{-1}$ (slat spacing / 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 spacing achieved a homogenous distribution of $UDI_{100\text{-}2000\ lx}$ across the length of the room. This is because the direct solar irradiation was strong in the IWEC weather data year (as shown in Table 3), leading to a significant number of hours of over supply (i.e. $UDI_{>\ 2000lx}$) despite undergoing attenuation in the diffusing PS-TIM unit.

To conclude, both the solar irradiation intensity, which impacts on the quantity of light coming into the room, and the solar altitude angle which additionally affects the penetration and distribution of light into the room, influences the process of selecting an optimal slat spacing for a window integrated with PS-TIM.





(e)

Fig. 5: *UDI* distribution in the office for double glazing and PS-TIM applied under different climates. The blue, green and red lines represent undersupplied UDI, useful UDI and oversupplied UDI, respectively.

3.1.2 Daylight comfort

The *uniformity ratio* (UR) [32], a metric associated with daylight distribution, was obtained from the minimum and area-weighted average illuminance values from the 45 hourly daylight study points for all double glazing and PS-TIM combinations as modified by the five selected climates (Fig. 6). Whilst BREEAM recommends that the uniformity ratio must exceed 0.3 to be classed as good practice [33], the CIBSE SLL Code for Lighting states that the minimum/average illuminance ratios on the working plane must not be less than 0.7 [34]. As such the more stringent UR threshold of 0.7 was used to evaluate the various glazing systems.

For all climates, double glazing failed to meet the UR criteria outlined in the SSL code. As can be seen from Fig. 6, for all climates, as slat spacing decreased, the percentage of working hours with higher uniformity ratios increased. Additionally, as latitude decreased, uniformity increased for a greater percentage of total working hours, once again reflecting the relationship between solar altitude and the light diffusing properties of the PS-TIM structures. Whilst these results suggest that PS-TIM structures will mitigate against the sharp illuminance contrasts normally found in naturally lit rooms incorporating normal transparent glazing systems, they do not indicate whether such homogenously lit conditions are desirable or not. To further explore the effect on issues such as visual comfort, a glare analysis was performed.

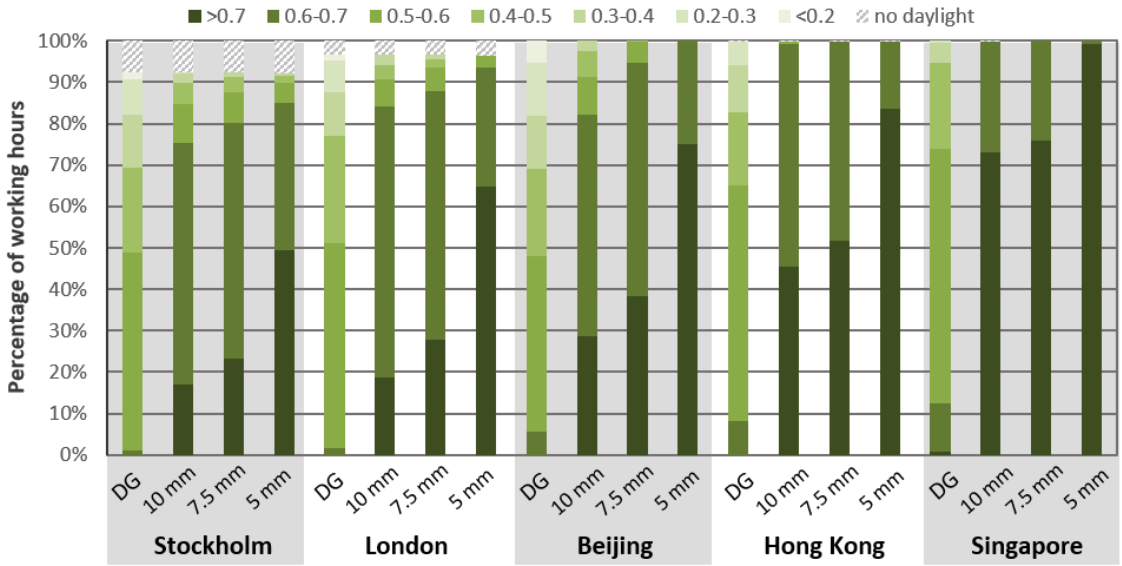


Fig. 6: Uniformity as a function of glazing type under different climate scenarios

Glare occurs when the luminance level within the field of view exceeds the brightness that the human eye can adapt to [35]. To evaluate glare, and in particular discomfort glare within the office space, the *Daylight Glare Probability* (*DGP*) technique was used [35]. Annual predictions [30, 31] of the *DGP* for both the double glazed and PS-TIM units were conducted for the selected cities at the view point (as illustrated in Fig. 4) and the results are shown in Fig. 7. When predicted for the double glazed window, *intolerable* glare ($DGP \geq 0.45$), *disturbing* glare ($0.4 < DGP < 0.45$), and *perceptible* glare ($0.35 < DGP < 0.4$) accounted for 15.9%, 12.6% and 11% of occupied hours respectively under Stockholm's climate. Apart from Beijing where the solar irradiation intensity and thus daylight availability were significant, as the latitude decreased, the data show that this generally resulted in an overall decrease in intolerable glare and improvements to glare ratings overall. This can be explained by the mid-day solar altitude being higher for lower latitudes which results in a reduction of direct solar radiation penetrating through the south-facing window system thus impacting less on the occupant's point in the room.

To evaluate the suitability of the various glazing units for use in design, a criterion threshold relating to the effectiveness of the daylit environment was established. To meet this threshold, over 95% of office hours must be classed as having *imperceptible* glare ($DGP \leq 0.35$) [31]. As can be seen from Fig. 7, for all cities, a PS-TIM slat spacing of 7.5 mm or less exceeded this criterion threshold. With respect to the 10 mm slat spacing, it only just fell short of meeting this threshold for Stockholm, London and Beijing but exceeded this threshold for those cities lower in latitude. At no point did the double glazed unit come close to meeting this criterion threshold.

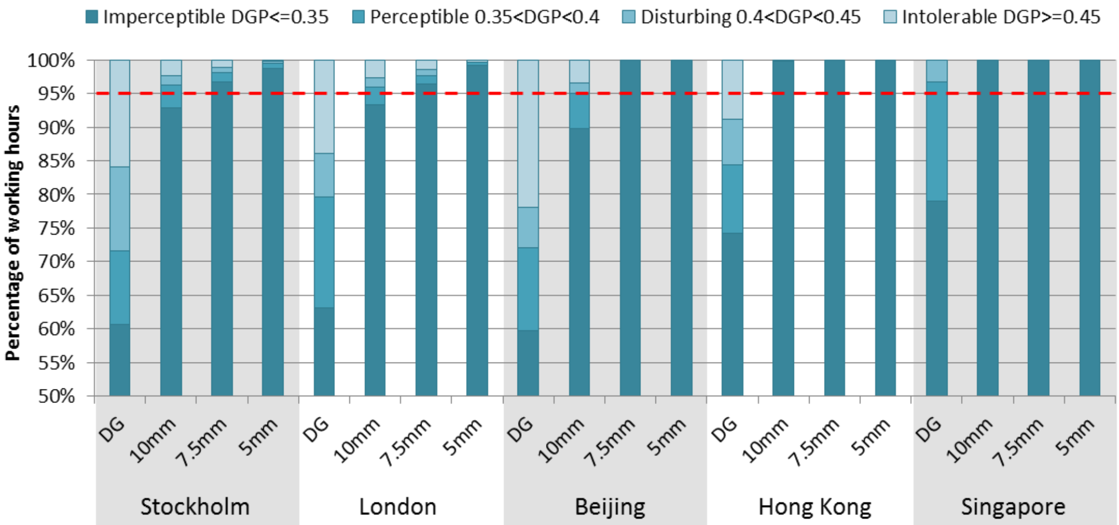
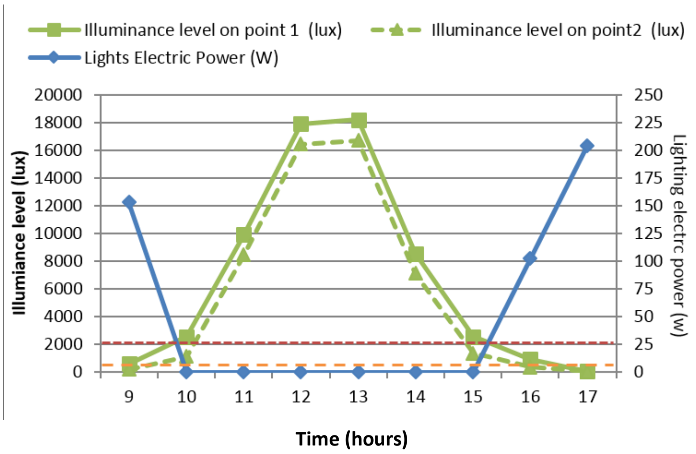


Figure 7: ***DGP*** **as a function of glazing type under the different climate scenarios**

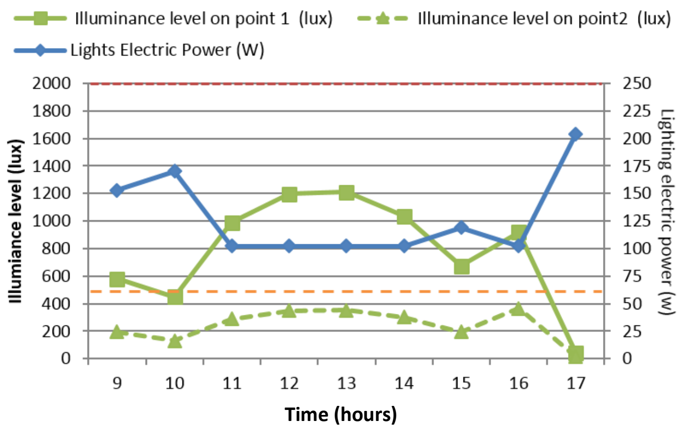
3.1.3 Requirement for interior shading to prevent strong daylight

In reality, if the illuminance levels caused by natural light through a window are excessively high or daylight-induced glare exists, occupants in a working space are likely to lower any interior shading devices (e.g. shade, blind or curtain). The shading device would therefore significantly reduce the transmission of daylight into the space, with illuminance levels deeper within the room possibly becoming insufficient for work. Consequently, artificial lighting would be required. To illustrate this, Fig. 8 shows an example of the hourly daylight illuminance levels as predicted for each sensor and the associated artificial lighting loads as modified by a double glazed unit in the office space for a typical sunny day. Showing with and without interior shade conditions, artificial lighting was switched on when the illuminance level dropped below 500 lx and therefore proving unsuitable for general task-related activities and switched off when illuminance levels exceeded 2000 lx, where over-illumination may prove problematic for the task at hand. A typical interior shade with a medium reflectance of 0.5 and low transmittance of 0.1 was used in the simulation.

From Fig. 8 (a), it can be seen that without the interior shade, illuminance levels at points 1 and 2 for the whole period from 10:00 to 15:00 were above 2000 lx, which was higher than the occupants' acceptance level. From Fig. 8 (b), when the interior blind was deployed, it blocked the strong daylight that occurred from 10:00 to 15:00, with the illuminance levels at point 1 within desirable acceptance thresholds for the whole working period from 09:00 to 16:00. Deeper into the room, at point 2, illuminance levels dropped below the desired lower acceptance threshold of 500 lx therefore requiring supplementary artificial lighting to illuminate this daylight zone. In turn this supplementary lighting requires electrical energy which when combined with its impact on heating and cooling loads affects the building's energy consumption overall.



(a)



(b)

Fig. 8: Lighting power and illuminance levels at points 1 and 2 (a) without interior shade and (b) with interior shade on a typical sunny day for the double-glazed unit.

From this initial shading device analysis, further simulations were performed on all glazing units for the five climate scenarios. These sought to explore the average number of hours per week that additional shading was needed to minimise the oversupply of daylight and maintain visual comfort. To do so, two daylight metrics with lower limit thresholds were used to control the shading strategy; (1) a UDI greater than 2000 lx and (2) a DGP greater than 0.35. If predicted values exceeded these lower limit thresholds, shading was deployed.

As can be seen from Fig. 9, double glazing invariably had the highest number of hours requiring the deployment of shading devices. Given that the PS-TIM structures are in effect interstitial shading devices, it is unsurprising to find that less shading was required in all climate types. With the 10 mm PS-TIM structure requiring the most additional shading in all climate types, as slat spacing reduced so did the requirement for additional shading. For example, when using the 7.5 mm PS-TIM structure, this reduced the requirement for additional shading to under 5 h per week for Stockholm, London and Beijing while totally eliminating the requirement for interior shade in Hong Kong and Singapore. Using the 5 mm PS-TIM virtually eliminated the requirement for additional shading in all climate scenarios. Overall the results suggests that the presence of PS-TIMs effectively reduces the requirement for additional shading under all climates scenarios, with decreasing slat sizes proving to be the most effective. However the results also demonstrate difficulties in using different daylight metrics in order to predict shading deployment, particularly for PS-TIM structures. For example when looking at ordinary double glazing, whilst it can be seen that the use of UDI invariably led to a longer deployment of additional shading over DGP, this could not be said for PS-TIM structures. It should also be mentioned that, for this research, only a typical shade with a medium reflectance of 0.5 and low transmittance of 0.1 was used. Further studies are therefore required to look at the relationship between reflectance and transmittance and daylight illumination on the working plane for PS-TIM structures.

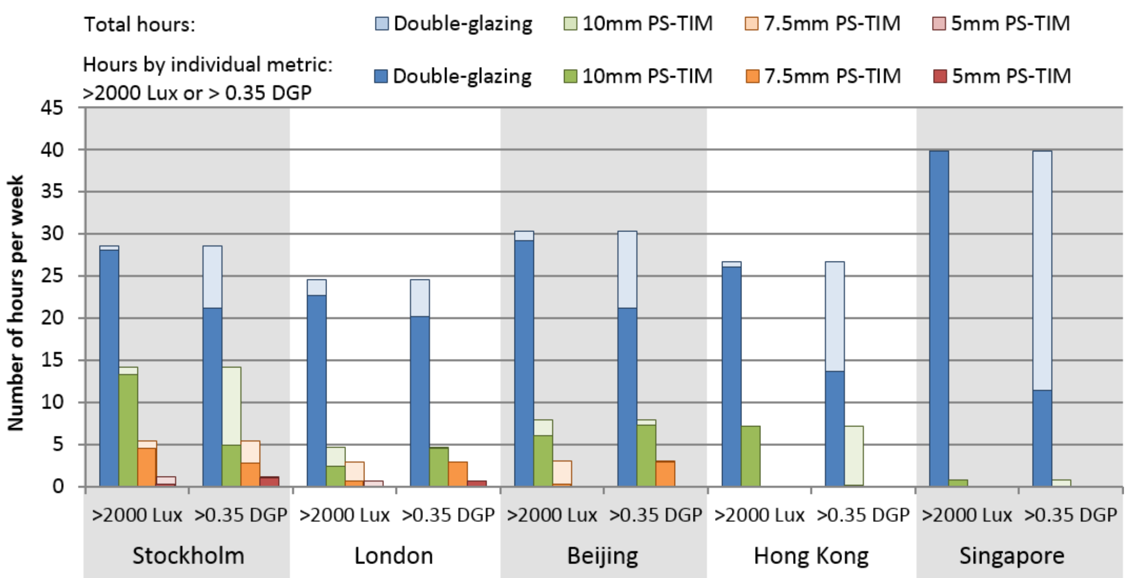


Fig. 9: Average number of hours per week when discomfort daylight condition exists

3.2 Heat loss and heat gain through windows with PS-TIM

To explore the key heat transfer paths that had a significant impact on the office's energy loads, a breakdown of annual heat loss and heat gain for conventional double glazing is shown in Fig. 10. Under the specific assumptions in this simulation, the total heat gain through the window (i.e. 'transmitted solar' plus 'window other') accounted for approximately 60% of total heat gain in all five climate conditions, in which the solar energy transmitted through the window accounted for between 29% and 48% of total heat gains. Similarly, aside for Singapore, heat loss through the window accounted for in excess of 50% of total losses across all climates. These results imply that strategies for improving solar control and/or increasing the thermal resistance of the conventional double glazed unit have the potential to significantly reduce the building's heating and cooling load.

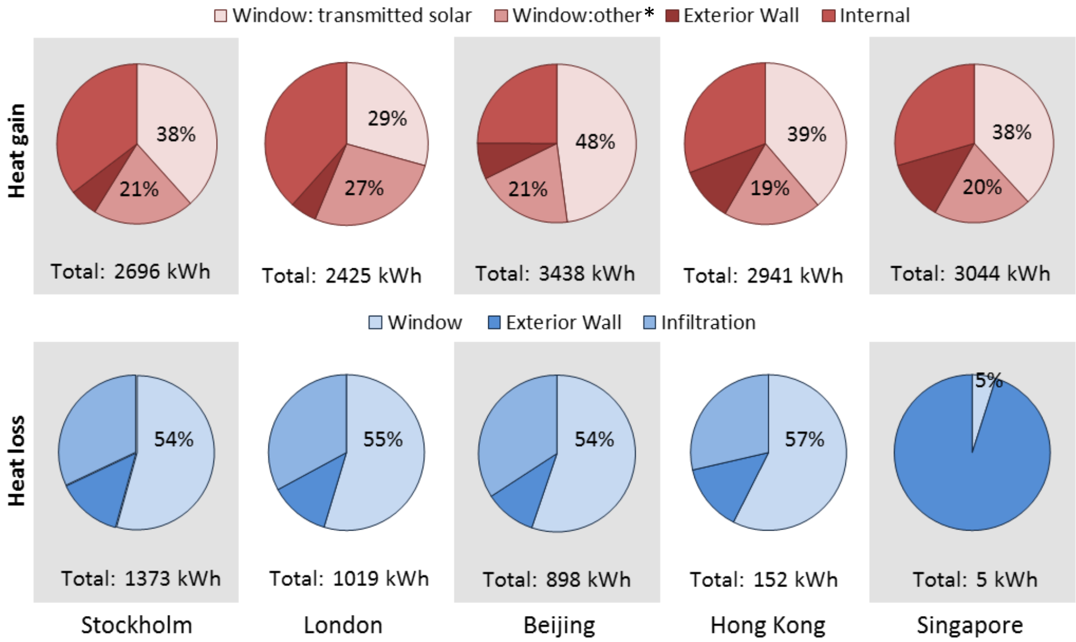


Fig. 10: Breakdown of annual heat loss and heat gain for the office with normal double glazing under five different climates

Fig. 11 illustrates the predicted heat losses and gains for all glazing combinations under the five climate scenarios. As can be seen from Fig. 11(a), the potential to reduce heat gains increased with decreasing slat spacing, this applicable across all climate scenarios. All in, average reductions in heat gains of approximately 38%, 42% and 46% for the 10 mm, 7.5 mm and 5 mm PS-TIMs respectively were obtained when compared to ordinary double glazing. Similarly, with respect to heat loss, the average reduction in heat loss was approximately 23%, 25% and 30% respectively. From these data, the presence of PS-TIMs within the glazing unit have a more profound influence on window heat gain than window heat loss in all climates. This can be explained by window heat gain being dominated by directly transmitted solar radiation, this reduced by the

*: this comprises indirect window heat gain, including conductive, convective and radiative window heat gain

presence of the translucent parallel slats within the glazing unit. In contrast, although the presence of PS-TIM increased the thermal resistance from one glazing pane to the other, the overall heat loss through the double glazed window was also significantly affected by the convective heat transfer on the external glazing's surface (i.e. the exterior surface convective heat transfer coefficient is determined by the wind speed as well as the temperature difference between the window surface and ambient environment).

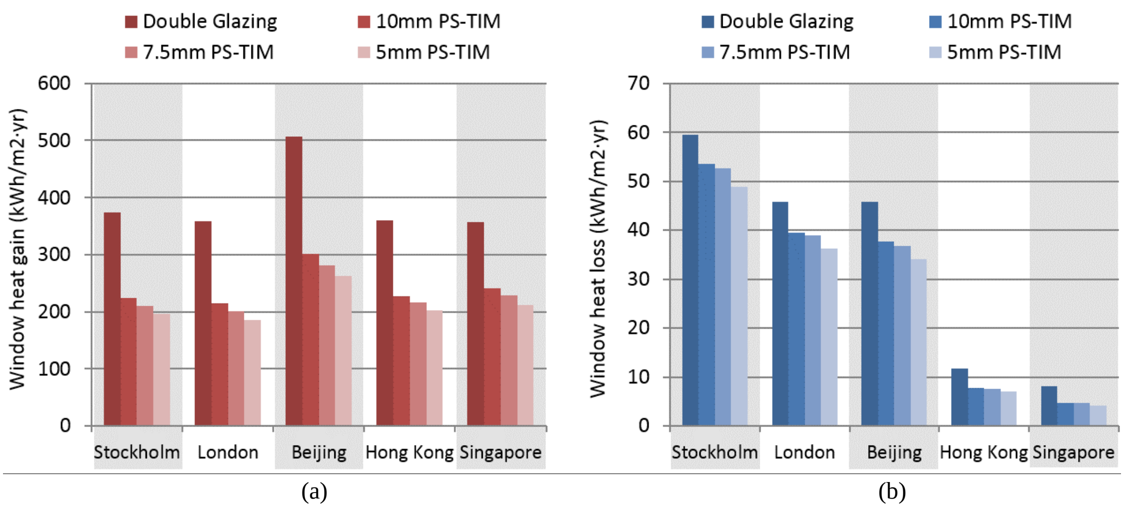


Fig. 11: (a) heat gain and (b) heat loss through windows (kWh/m^2·yr) after applying different configurations of PS-TIM under five climates

3.3 Energy performance after applying PS-TIM

Whilst the presence of PS-TIMs significantly affected overall window heat losses and gains, these results do not indicate whether these effects are beneficial or not. To explore this further, the total energy consumption of the office was predicted and the results can be found in Fig. 12. This simulation considered not only the four glazing types under the five climate scenarios but also included the realistic scenario where interior shading would be deployed for the double glazing unit if the space was either deemed to be over-illuminated or experiencing glare. To gain a fuller understanding of the impact of the various factors at play, two HVAC operation schedules were considered; (1) where the HVAC system operated only during the working hours of

09:00-17:00 on weekdays and (2) where the HVAC system was under continuous operation.

As can be seen from Fig. 12, when the HVAC system was in operation during normal working hours, the 10 mm PS-TIM gave rise to the lowest energy consumption of all glazing combinations under all climates tested. When compared to the double glazed unit with the interior shade deployed, energy consumption was reduced by between 13.7 and 18.6%, the majority of which due to reductions in both lighting and cooling loads. However when compared to ordinary, unshaded double glazing, it is evident that whilst lighting loads increased for all climates, cooling demands reduced significantly therefore cooling proved to be the dominant mechanism through which savings were made. Interestingly whilst the results showed that decreasing PS-TIM slat spacing did result in lower heating energy consumption, there was a minimal to negligible difference between the glazing unit combinations. For example, when applying the 10mm PS-TIM to the London scenario, a 25.7% reduction in lighting energy and 24.6% reduction in cooling energy was observed. However only 2.4% of heat energy was saved. As such, for this particular study, the presence of PS-TIMs do not offer any tangible benefits with respect to reducing overall heating demand. This can be explained by the fact that, although the interstitial PS-TIM structure reduces the internal heat loss through the window, it simultaneously reduces the solar heat gain that is transferred from the window to the room during daytime for passive heating, this evident in the hourly plots for two winter days in Fig. 13. The balance between these two is therefore not sufficient to yield a significant reduction in heating demand when the HVAC system is in operation only during working hours on working days.

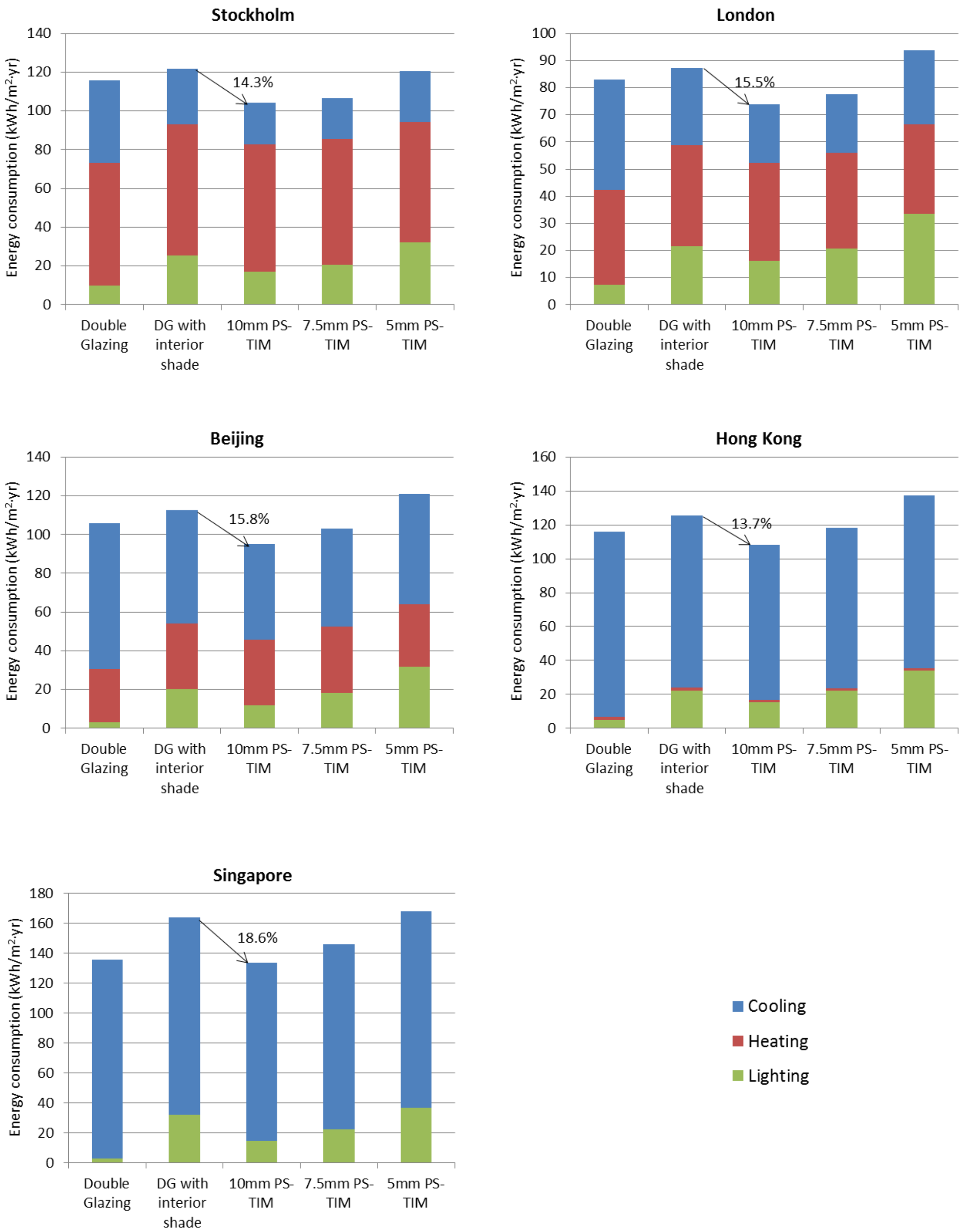


Fig. 12: Annual heating, cooling and lighting energy consumption when HVAC system operates between 09:00-17:00 on workdays.

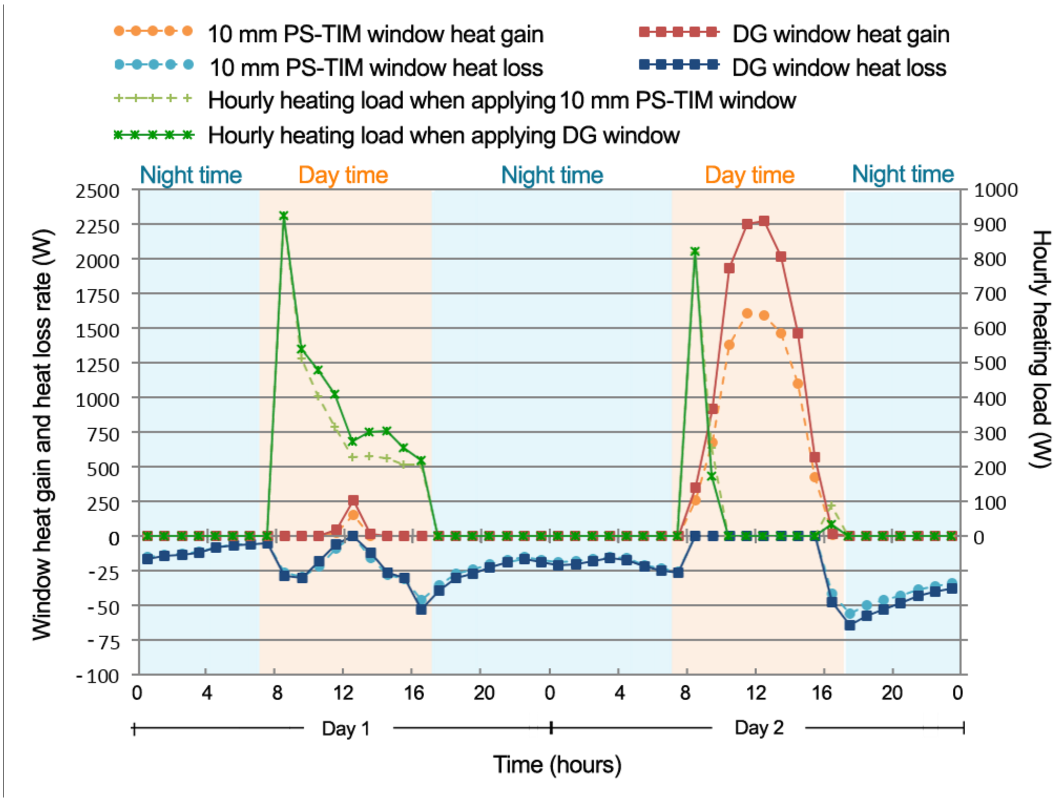
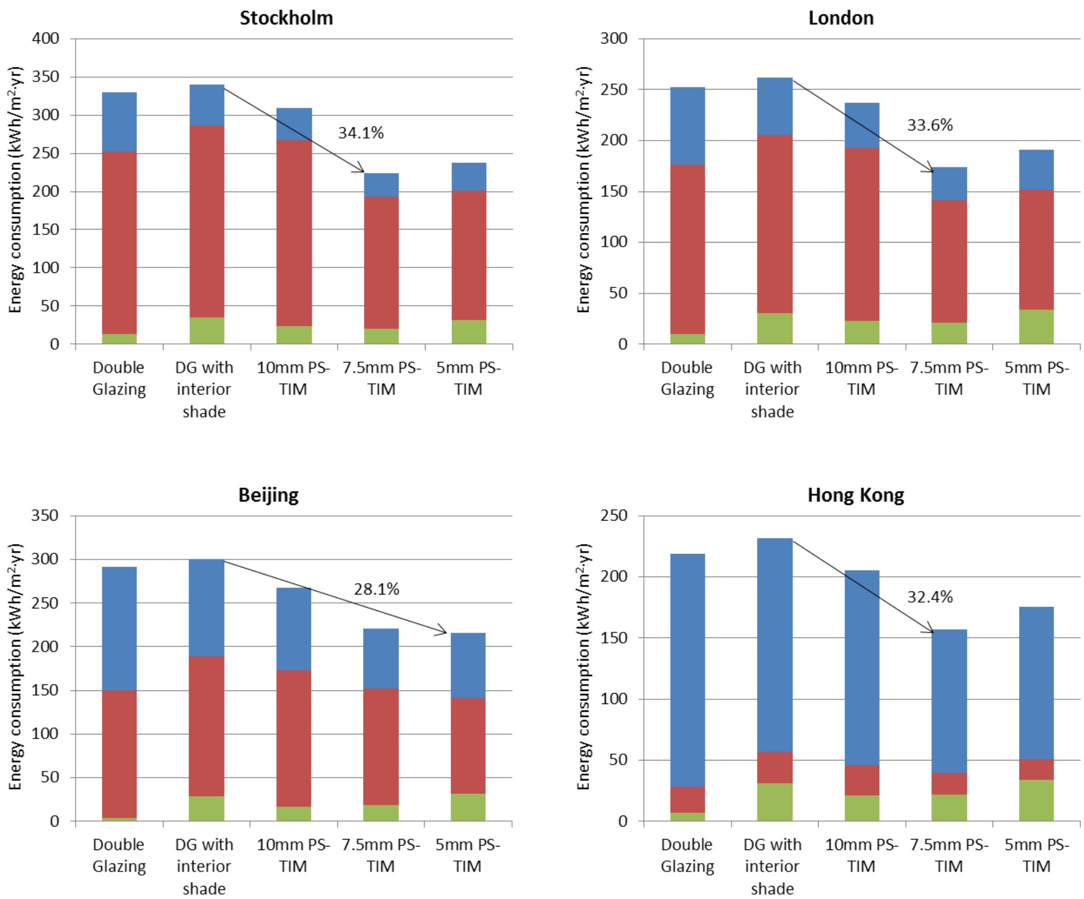


Fig. 13: Hourly window heat gain, heat loss and space heating load for window system with and without PS-TIM when HVAC system operates between 09:00-17:00 on workdays on two winter days.

When the HVAC system was in operation continuously throughout the year, the true benefits of TIMs were observed with respect to overall energy consumption (Fig. 14). For all cities, PS-TIM-based glazing units outperformed both shaded and unshaded double glazed units, with the 7.5 mm PS-TIM structure providing the best energy saving potential under all climates except Beijing, where the energy consumption of the 5 mm slat spacing proved to be marginally lower than the 7.5 mm configuration. A close inspection of the data revealed that under all climates, the 7.5 mm slat spacing gave the highest reduction in cooling demands across all scenarios, with the 5 mm slat spacing proving to result in the largest heating demand savings. Interestingly, under all year HVAC operation, the results clearly show that PS-TIM-based structures do indeed provide significant savings with respect to heating energy consumption. When compared to shaded ordinary double glazing for Stockholm, London, Beijing and Hong Kong, the 7.5mm slat spacing reduced heating demands by 31%, 31%, 17.1% and 30.5% and for the 5 mm slat spacing, 32.4%, 32.5%, 32.1% and 31.9% respectively. The reason behind the improved performance of PS-TIMs with smaller slat spacings is that their increased thermal resistance results in a dramatic reduction to overall heat loss during night time for heating dominated climates, and a reduction in heat gains for cooling dominated climates. In so doing, this significantly reduces the heating and cooling demands during the night when the HVAC system is always on. This can be seen from Fig. 15, which illustrates the hourly heat gains, losses and space heating energy consumption for a window with and without the 7.5 mm PS-TIM on two winter days (48 h). From these results, the application of PS-TIMs to this specific office example can provide a reduction in energy consumption from 28.1% to 35.8%.



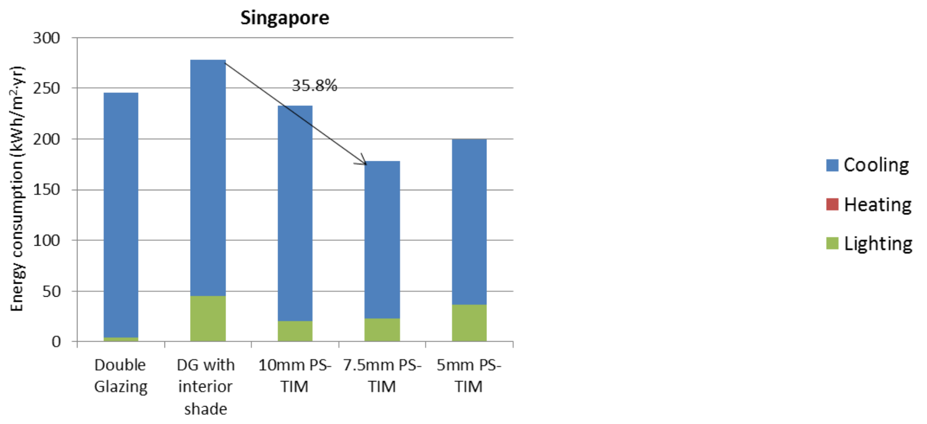


Fig. 14: Annual heating, cooling and lighting energy consumption when HVAC system is always on.

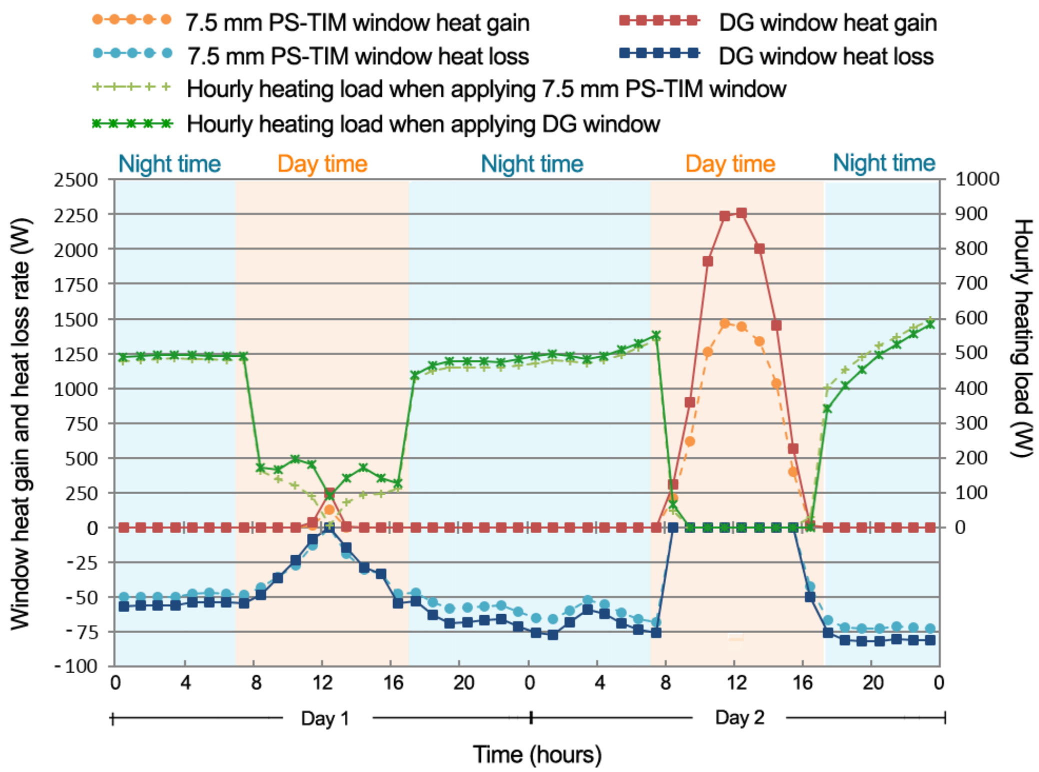


Fig. 15: Hourly window heat gains, losses and space heating loads for window systems with and without 7.5 mm PS-TIM when HVAC system is always on for two typical winter days

4. Conclusion

EnergyPlus accompanied by a Computational Fluid Dynamics thermal model and a ray-tracing optical model were used to predict the building performance of window systems with and without the incorporation of Parallel Slats Transparent Insulation Materials (PS-TIM) for a small office subject to five climate conditions. Their impact on window heat gains and losses and on overall heating, lighting and cooling energy consumption was analysed. RADIANCE was used to predict lighting performance with respect to key daylighting and comfort metrics.

The results clearly show that the specification and application of glazing systems, especially those containing PS-TIMs is complex and dependent on a number of interrelated factors, and that these must be understood by the designer if they are to be successfully incorporated into a building. For the specific office under test, it was observed that when compared to ordinary double glazing, smaller slat spacings yielded the most useful daylight, and reduced the occurrence of over illumination or visual discomfort. Similarly, given that PS-TIM structures effectively comprise a series of horizontal blinds encapsulated within a cavity, their use resulted in an overall reduction in the necessity to deploy further shading devices, with smaller slat spacings resulting in lower heat gains in the order of 38% - 46% due to their interference with incoming solar radiation. The shading potential of PS-TIM structures and their relationship with slat spacing was shown to be important as latitude increased. Conversely our results also showed that smaller slat spacings gave rise to lower heat losses in the order of 23% to 30%, a product of the interstitial air cavity being broken into small, horizontal linear cells where the cell walls provide additional viscous resistance to the onset of free convection, interfering with thermal radiation transferred from one pane of the glazing unit to the other, thereby increasing the thermal resistance of the glazing system. Overall, the presence of the PS-TIM had a more profound influence on window heat gain than on heat loss in all climates.

Beyond these observations, our results clearly demonstrated that the effectiveness of TIM-based systems was also a function of the heating and cooling (HVAC) schedule in operation. In the case of intermittent (daytime) operation only, whilst a 10 mm PS-TIM slat spacing gave rise to the lowest energy consumption overall (up to an 18.6% improvement), smaller slat spacings gave rise to equivalent if not increased energy consumption over double glazed units. One of the key driving forces behind this increase was the additional need for artificial lighting under such conditions and the negligible difference in heat gains due to the slats interfering with incoming solar radiation. However the true benefits of the PS-TIM system were evident when the HVAC system was under continuous operation. Here the 7.5 mm PS-TIM proved to yield the lowest overall energy demands, with a significant proportion of energy being saved at night due to the increased thermal resistance of the PS-TIM structure thus mitigating against night time heat loss, or in the case of a climate such as Singapore against night time heat gains. Energy savings for this particular operation schedule ranged from 28.1% to 35.8% overall.

In conclusion, the use of PS-TIMs over conventional glazing units offer a range of benefits to the occupants of buildings, with their use and specification depending on the priorities of the design team. Our research shows that for the case study office, either the 10 mm or 7.5 mm slat spacings may provide the best compromise between energy consumption and daylight metrics associated with daylight distribution and visual comfort. However, these results do not consider whether the environment created, and in particular whether the more qualitative aspects of the daylit environment such as view or uniformity are either suitable or desirable

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Appendix:

(1) The equivalent thermal conductivity of air cavity in double glazing unit (DG)

ΔT \ $\bar{T}$	-15	-10	-5	0	5	10	15	20	25	30	35
5	3.99	4.13	4.27	4.43	4.60	4.78	4.97	5.16	5.37	5.59	5.82
10	4.31	4.44	4.58	4.73	4.90	5.07	5.25	5.45	5.65	5.86	6.09
15	4.57	4.70	4.83	4.98	5.14	5.31	5.49	5.67	5.87	6.08	6.30
20	4.78	4.90	5.03	5.18	5.33	5.49	5.66	5.85	6.04	6.24	6.46
25	4.93	5.05	5.18	5.31	5.46	5.62	5.79	5.97	6.15	6.35	6.56

(2) The equivalent thermal conductivity of the air cavity between two panes with 10 mm PS-TIM (10 mm PS-TIM)

ΔT \ $\bar{T}$	-15	-10	-5	0	5	10	15	20	25	30	35
5	3.73	3.83	3.95	4.06	4.18	4.30	4.44	4.57	4.71	4.85	5.00
10	3.82	3.93	4.04	4.16	4.28	4.40	4.53	4.66	4.80	4.94	5.08
15	3.94	4.05	4.16	4.28	4.40	4.51	4.64	4.77	4.91	5.05	5.19
20	4.08	4.18	4.30	4.41	4.53	4.65	4.77	4.90	5.04	5.17	5.31
25	4.21	4.32	4.43	4.54	4.66	4.78	4.90	5.03	5.16	5.30	5.44

(3) The equivalent thermal conductivity of the air cavity between two panes with 7.5 mm PS-TIM (7.5 mm PS-TIM)

ΔT \ $\bar{T}$	-15	-10	-5	0	5	10	15	20	25	30	35
5	3.64	3.75	3.86	3.98	4.09	4.21	4.33	4.44	4.56	4.71	4.86
10	3.66	3.77	3.87	3.99	4.10	4.22	4.35	4.46	4.58	4.72	4.87
15	3.69	3.80	3.90	4.01	4.13	4.24	4.35	4.48	4.60	4.75	4.90
20	3.73	3.83	3.94	4.05	4.16	4.27	4.39	4.51	4.64	4.79	4.93
25	3.77	3.87	3.98	4.09	4.20	4.32	4.43	4.55	4.68	4.83	4.97

(4) The equivalent thermal conductivity of the air cavity between two panes with 5 mm PS-TIM (5 mm PS-TIM)

ΔT \ $\bar{T}$	-15	-10	-5	0	5	10	15	20	25	30	35
5	3.48	3.58	3.68	3.77	3.87	3.98	4.09	4.20	4.32	4.44	4.57
10	3.48	3.58	3.67	3.77	3.87	3.98	4.09	4.20	4.32	4.44	4.57
15	3.48	3.58	3.67	3.78	3.88	3.98	4.09	4.21	4.32	4.44	4.56
20	3.49	3.58	3.68	3.78	3.88	3.99	4.09	4.21	4.33	4.45	4.57
25	3.49	3.59	3.68	3.78	3.88	3.99	4.10	4.21	4.33	4.45	4.57