Development of a comprehensive method to analyse glazing systems with Parallel Slat Transparent Insulation Material (PS-TIM)

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Abstract

In order to provide enhanced levels of indoor comfort and building energy conservation, significant improvements have been made in the design of glazed facades and window systems, yielding increases in thermal resistance while simultaneously maintaining access to daylight. Some of these approaches result in glazing systems with relatively complex structures and it is difficult to characterise their optical and thermal properties for use in building simulation. In this research, a comprehensive model has been developed to accurately predict the thermal and optical properties of complex glazing systems, and a workflow developed to yield detailed daylight and energy performance (heating, cooling and lighting) predictions of these systems when applied in buildings. Through this approach, the thermal characteristics of complex fenestration systems are obtained from validated Computational Fluid Dynamics model, and a ray-tracing technique is used to obtain *Bidirectional Scattering Distribution Function* (BSDF) data to represent their optical characteristics. These characterises may be used in building simulation software (in this case EnergyPlus) to obtain building heating, cooling and lighting energy estimates for a room incorporating complex glazing systems. Detailed visual comfort predictions including *useful daylight illuminance*, *daylight uniformity* and *glare* may also be made, using a complementary optical model run using RADIANCE simulation. This workflow is implemented to investigate a room served by different Parallel Slat Transparent Insulation Materials (PS-TIM), which represents an example of a complex fenestration system. The workflow is used to explore the effect of slat pitch (i.e. the distance between neighbouring slats) on predicted performance and was found to provide reasonable daylight and energy performance prediction. The results indicate that use of glazing systems with PS-TIM can provide homogenous daylight distribution and up to 33.6 % energy reduction when the simulation is run using weather data for London.

Keywords: Building Simulation; Transparent Insulation Materials; Dynamic Thermal Conductivities; Bidirectional Scattering Distribution Functions (BSDF); Thermal and Daylight Performance.

Nomenclature

Symbols

A	aspect ratio	-
$a - f$	coefficients for polynomial regression	-
D	daylight matrix	-
E_e	exterior IR incident on window plane	W/m^2
E_i	interior IR incident on window plane	W/m^2
E_v	vertical illuminance	lux
h	heat transfer coefficient	W/m^2 · K
i	illuminance at point of interest for a single time step	-
I	illuminance at point of interest for a time series	-
k	thermal conductivity	W/m·K
L	height of the window air cavity	m
s	width	M
	- also sky vector in equation (6)	-
S	radiation (short-wave, and long-wave from zone internal sources) absorbed by surface	W/m^2
	- also sky matrix in equation (7)	-
T	transmission matrix	-
t	temperature	K/℃
t_m	mean temperature	℃
Δt	temperature difference	℃
V	view matrix	-
ε	emissivity	-
σ	Stefan-Boltzmann constant	W/m^2·K^4
Gr	Grashof number	-
Nu	Nusselt number	-
Pr	Prandtl number	-

Subscripts

e	external
g	gap
i	internal
m	mean
s	interstitial structure/ slat
v	vertical
PS-TIM	Parallel Slat Transparent Insulation Material

1. Introduction

Buildings currently account for 30-40% of total energy consumption worldwide [1-4]. The design and specification of the building envelope is a major determining factor of building energy use during operation [5-7]. Windows in building envelopes play a critical role by determining the penetration of solar energy and daylight, controlling the view into and out of a building and influencing the overall building energy consumption [8-10]. Innovative window systems, where interstitial structures, such as horizontal Venetian blinds, pleated blinds, and Parallel Slat Transparent Insulation Materials (PS-TIM), are sandwiched between the panes of double glazed window are proposed as strategies to effectively reduce heat transfer, while maintaining access to daylight [11-21]. When exploring the performance of these complicated building elements in buildings, numerical simulation methods are indispensable in helping to create a detailed hour by hour picture of performance or to identify optimal design solutions using parametric analysis. Various building simulation tools, such as EnergyPlus, ESP-r, IES, TRNSYS, TAS and RADIANCE can be used to explore the energy, thermal and daylight performance for buildings with complex fenestration systems [1, 20, 22-26]. The challenges related to representing complex window systems in these simulation tools include: 1) precise characterisation of the thermal and optical characteristics of fenestration systems, in which two- or three-dimensional heat transfer and/or light transmittance might exist due to the presence of complex structural geometries; 2) the potential need to model adaptive features associated with the operation of complex fenestration systems (e.g. switchable glazing, moveable shading, etc.), that may affect a number of properties (e.g. thermal, visual) simultaneously.

Building energy simulation programs are not currently well set up for accurate modelling of these complex fenestration systems, often because of the simplified thermal and optical models used to solve heat transfer and light transmission. i.e. one dimensional methods are used for both heat transfer and light transmitted through fenestration systems [27]. Glazing systems with complex configurations are often represented using pre-computed solar heat gain coefficients and visible transmittances, which despite being determined using radiosity methods are none the less lacking in terms of representing the highly complex, angle-dependent interaction implicit when they are subject to realistic patterns of incident radiation [28, 29]. In addition, analysis is currently restricted to the geometric forms associated with blinds, shades and screens, and it is challenging to characterise less common structures (e.g. tubular shading structures, nonlinear shading systems, etc.). The launch of EnergyPlus V7.2 provided the capability to include Bidirectional Scattering Distribution Functions (BSDF) in the modelling process, and this has significantly enhanced the software's capability to predict building energy and daylighting performance of buildings with complex fenestration systems [27]. Published articles relating to the use of BSDFs in EnergyPlus are not common. This is, in large part, due to the challenge of obtaining the specific BSDF data for window systems under prediction [28, 30]. For the purpose of precisely modelling optical performance of complex fenestration systems in EnergyPlus, RADIANCE provides a ray-tracing tool to numerically calculate BSDFs and a software utility, WINDOW, establishes a bridge for its implementation in EnergyPlus [29]. Femandes et al. [31] have undertaken modelling using BSDFs to represent complex fenestration systems in order to quantify the potential of energy saving and peak demand reduction in a space served by an angular selective window system (i.e. expanded metal mesh, tubular shading structures, and micro-perforated screens). The results revealed that energy savings of between 28 ~ 47% may be achieved in the perimeter zone when applying the angular selective window system under the climates of Chicago and Houston. Hoffmann et al. [32] investigated the impact of twelve different shading devices on whole building energy performance under the moderate San Francisco climate and a hot and dry Southern California climate. They used their study to develop optimised strategies to balance solar gain with glare and daylight levels. The optical properties of the shading systems were defined using the BSDF method and hourly scheduled surface gains. The results showed that shading geometry and slat material characteristics significantly affected the amount of heat gain from solar radiation and distribution of transmitted daylight.

When dealing with adaptive fenestration systems, models need to accommodate the changes in window thermo-optical properties that occur in response to changes in energy flux incident on the building. Firlag, et al. [33] investigated the use of dynamic control algorithms (using the Energy Management System (EMS) feature in EnergyPlus) to control an external roller blind mounted onto a double-glazed window, as well as an inter-pane cellular shading device within a triple-glazed window. Both systems were applied to a typical residential building and simulated under four different climates (i.e. Atlanta, Minneapolis, Phoenix and Washington DC), respectively. They also used BSDF data to represent the window systems and linked these to algorithms that simulated dynamic controls. It was concluded that using automated shading devices with the proposed control algorithms can reduce solar heat gain, resulting in a 11.6 ~ 13.0% reduction in building energy consumption.

In practice, the integration of an interstitial structure within the air cavity of a double glazing unit not only influences solar gain, it also has a significant effect on the free convection and long-wave radiative heat transfer between the two panes of glass. Although, efforts have been made to combine *BSDFs* with building energy simulation [26, 32, 33] to achieve a more accurate representation of solar gains (as well as daylight distribution) within the analysis of building employing complex fenestration systems, the effect of these interstitial structures on free convection and long-wave radiation heat transfer within the glazing cavity has not been considered. In practice, these greatly affect thermal and energy predictions [11, 12].

This paper proposes a method that offers a comprehensive representation of complex fenestration systems applied buildings. The approach differs from previous studies through the inclusion of a comprehensive model to represent thermal behaviour and its combination with an effective method for representing optical performance within existing building energy performance software. Computational Fluid Dynamics modelling is used to determine the thermal characteristics and a ray-tracing technique is used to predict the optical characteristics what are then converted into a BSDF format. All of these were input into building simulation software, EnergyPlus, to obtain building heating, cooling and lighting energy estimates, when complex fenestration systems are applied within the window of a typical office. The luminous environment is explored through the use of *useful daylight illuminance* (*UDI*), *daylight uniformity* and *daylight glare probability* [1, 34-37], based on a complementary optical model using RADIANCE simulation.

2. Analysis method

This paper presents a workflow that incorporates the thermal and optical characteristics of complex fenestration system within EnergyPlus and RADIANCE using a typical office space as a case study to explore its implementation. Three glazing systems with Parallel Slat Transparent Insulation Material (PS-TIM), shown in Figure 1, are used to illustrate how the model might be used. The material that forms the parallel slats is assumed to be a Lambertian diffuser with 50% transmittance, as it can provide homogeneous daylight distribution within a space. For more information on this PS-TIM system, refer to the authors' previous publications [12, 20].

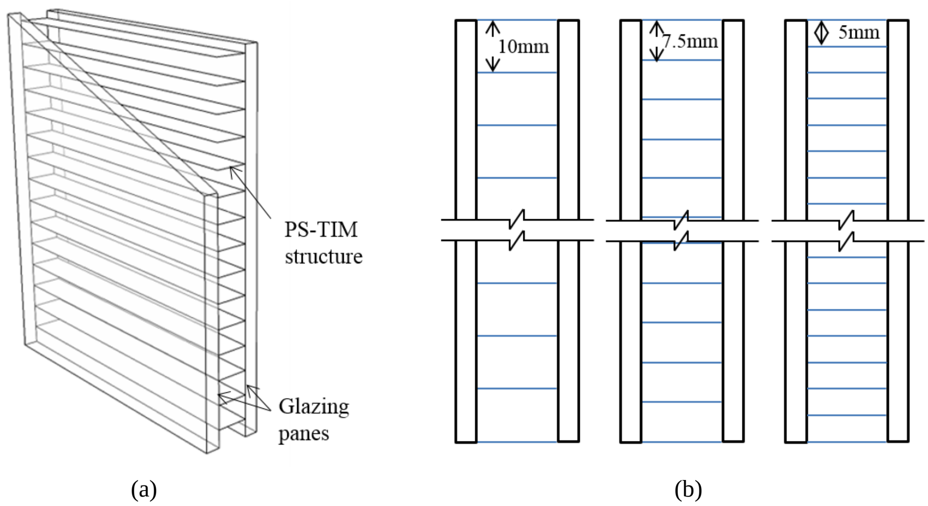


Figure 1 (a) PS-TIM structure in a double-glazing unit; (b) 2D schematic illustrating the geometry of the glazing system integrating PS-TIM with 10mm, 7.5mm and 5mm slat pitches

2.1 Overview of the analysis method

The workflow that sits behind the holistic analysis method consists of four major blocks as shown in Figure 2:

1) a fenestration thermal model where a two-dimensional Computational Fluid Dynamics (CFD) simulation has been used to investigate the dynamic thermal conductance across

the glazing system driven by variation in environmental conditions (i.e. different glazing average temperature and temperature difference across the glazing panes);

2) a fenestration optical model where a ray-tracing technique has been used to obtain *Bidirectional Scattering Distribution Functions* (*BSDFs*) based on the geometry and optical properties of the glazing system;

3) a building energy simulation where the optical and thermal characteristics of the glazing system obtained from the previous thermal and optical models are applied within EnergyPlus to obtain building energy performance under imposed climatic conditions;

4) a complementary building daylight simulation where the *BSDF*s for the glazing system are used in an annual analysis that uses hourly solar irradiance data in RADIANCE to provide a detailed picture of daylight performance.

This analysis method will yield a building energy performance prediction (i.e. heating, cooling and lighting energy consumption) and detailed picture of daylight performance (i.e. useful daylight illuminance, daylight glare probability, etc.). More information on each of the blocks within the workflow shown in Figure 2 are provided in the next sections.

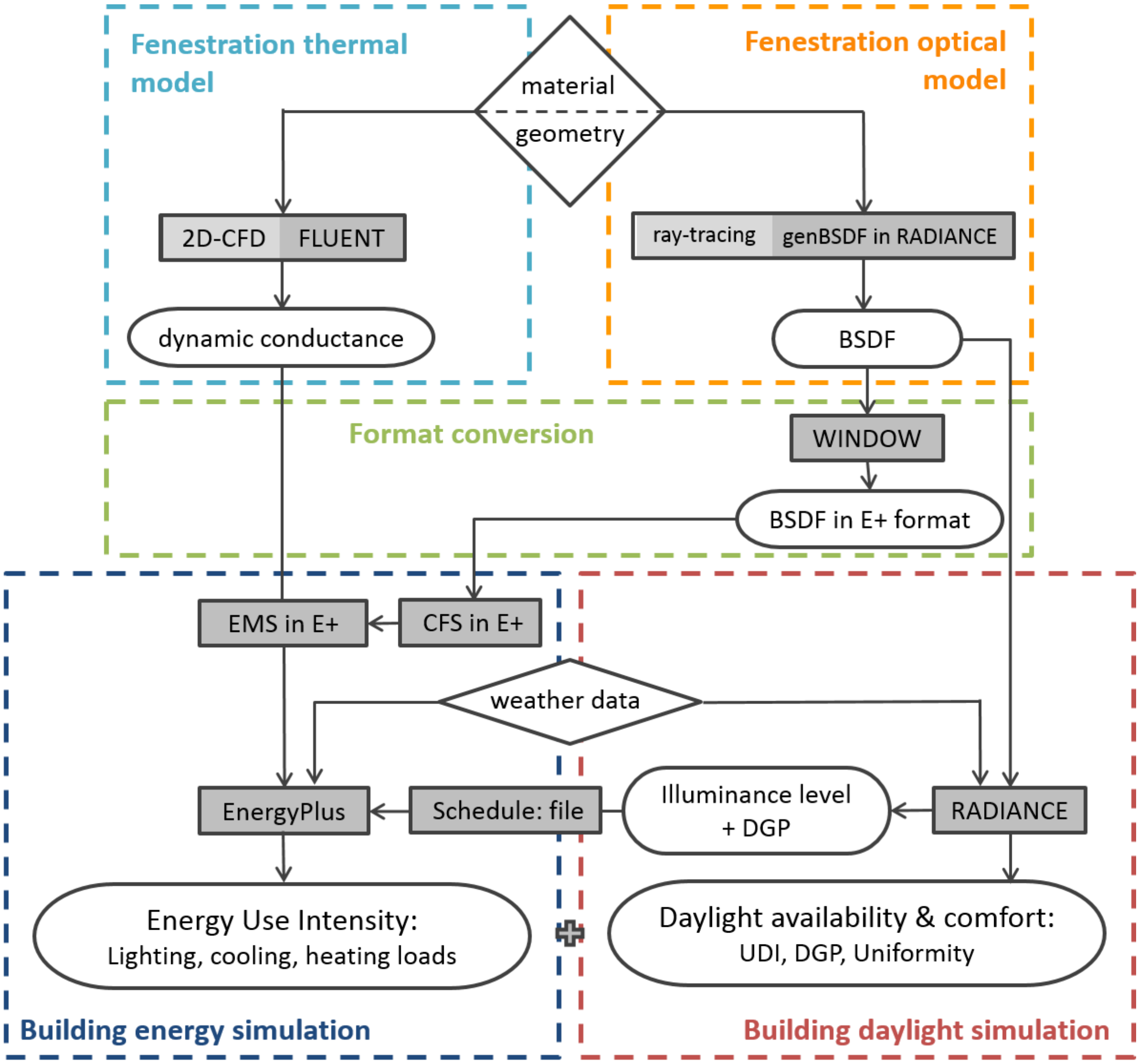


Figure 2: Flow chart of the workflow for modelling complex fenestration*

2.2 Fenestration thermal model

Through understanding the default algorithm within EnergyPlus that is used to predict the energy performance of glazing systems in buildings, the concept of characterising the dynamic thermal behaviour of complex glazing systems is proposed in this section to expand the capability of EnergyPlus. This section also describes how CFD (in this case ANSYS FLUENT 15.0) is used to generate the dynamic thermal characteristics of a PS-TIM

*: 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 (i.e. presenting each state of a complex glazing system); 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*.

glazing unit so that it can be represented in an EnergyPlus simulation.

2.2.1 Glazing heat transfer equations in building performance simulation (EnergyPlus)

EnergyPlus, which has been widely adopted for the prediction of building energy performance [1], is a heat balance based simulation program that yields space heating and cooling loads [38]. When solving for heat transfer through fenestration systems within EnergyPlus, the heat flow is assumed to be one dimensional and perpendicular to the glazing panes. A schematic diagram detailing the heat transfer in a double glazing system is presented in Figure 3 (a). The heat balance equation for each of the glazing unit's surfaces can be written as:

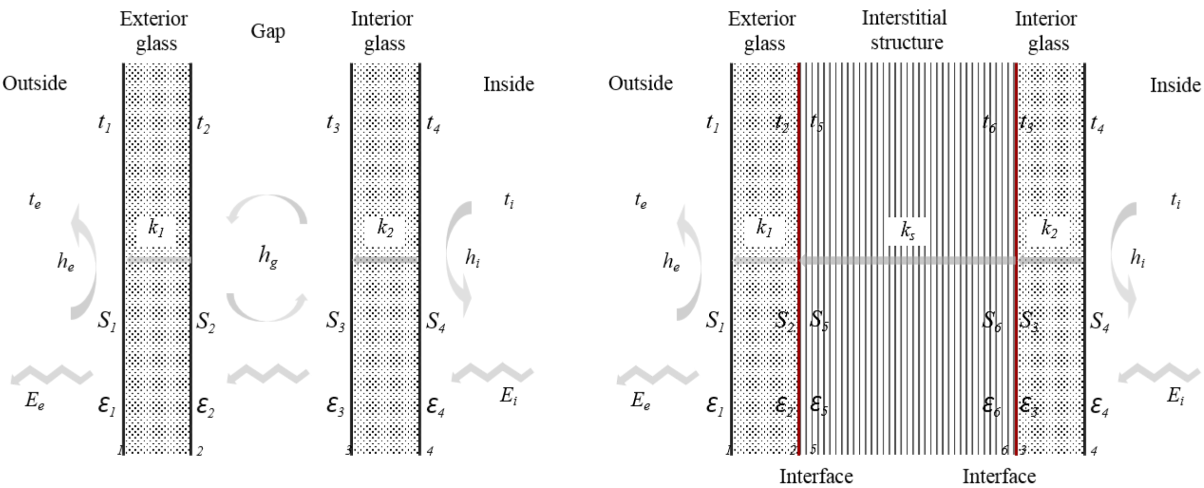


Figure 3: Demonstration of heat transfer and the variables used in heat balance equations for (a) double-glazed window (b) double glazed window system with an interstitial structure.

$$E_e\varepsilon_1 - \varepsilon_1\sigma t_1^4 + k_1(t_2 - t_1) + h_e(t_e - t_1) + S_1 = 0 \tag{1}$$

$$k_1(t_1 - t_2) + h_g(t_3 - t_2) + \sigma\frac{\varepsilon_3\varepsilon_2}{1-(1-\varepsilon_2)(1-\varepsilon_3)}(t_3^4 - t_2^4) + S_2 = 0 \tag{2}$$

$$k_1(t_4 - t_3) + h_g(t_2 - t_3) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_3)(1-\varepsilon_2)}(t_2^4 - t_3^4) + S_3 = 0 \tag{3}$$

$$E_i\varepsilon_4 - \varepsilon_4\sigma t_4^4 + k_2(t_3 - t_4) + h_i(t_i - t_4) + S_4 = 0 \tag{4}$$

The convective heat transfer coefficient (h_g) for the gas cavity between two glazing panes is represented by the non-dimensional *Nusselt number* ($h_g = Nu\frac{k_g}{s}$), while the strength of radiative heat transfer across the gas cavity is determined by the emissivity of the two glazing surfaces that enclose it and the view factors between them.

However, when a complex structure such as PS-TIM is present within the gas cavity, it provides additional resistance to convection and interferes the radiative heat transfer between the two glazing panes. The strength of the heat transfer depends on the geometry and thermophysical properties of the interstitial structure. EnergyPlus simplifies the heat transfer process by assuming the two-dimensional characteristics of the interstitial structure may be represented by a single solid layer, similar to a glazing pane (illustrated in Figure 3 (b)). It achieves this by applying an equivalent thermal conductivity (k_s) to represent the combined convective and radiative heat transfer through the complex gas/structural element.

Normally, the equivalent thermal conductivity of the interstitial layer (k_s in Figure 3 (b)) is obtained by following the method described in ISO 15099 [39]. In this, radiative heat transfer is calculated using a radiosity method based on the thermal radiation properties of structure and natural convection within the interstitial structure is calculated using a simple model. However, previous researchers [11, 12, 40-44] have shown that natural convection within the geometry of a complex interstitial shading device can vary significantly under dynamic boundary conditions (e.g. internal and external glazing pane temperature, average temperature of the interstitial structure), and these significantly affect the overall thermal conductance of the interstitial gas/structural layer.

Thus, neither the standard method, which does not consider the effect of gas movement within the interstitial structure on heat transfer, nor using a single equivalent conductivity, which does not reflect dynamic boundary condition, would result in an accurate prediction of the heat transfer. CFD calculation, as presented in section 2.2.2, is a recognised method that has been widely used to predict the thermal behaviour of complex fenestration systems. Equivalent thermal conductivities under different thermal conditions can be obtained by varying the boundary conditions in the CFD calculation. Thus, a series of individual values can be employed to represent the dynamic thermal conductivity in building simulation.

2.2.2 Dynamic thermal properties acquiring method (CFD)

A validated two-dimensional finite volume model [11, 12] developed using the CFD software, FLUENT, was used to determine the conductive, convective and radiative heat transfer through the complex fenestration systems shown in Figure 1. These contain PS-TIM with slat pitches of 5mm, 7.5mm and 10mm that and are explored later in this paper to illustrate implementation of the workflow illustrated in Figure 2.

To simplify the CFD simulation process, the following assumptions were made: 1) the internal surfaces of the left and right glazing panes were set as two isothermal walls with different temperatures (i.e. interface of surface 5 and 2, and interface of surface 6 and 3 highlighted in red in Figure 3 (b)), while the top and bottom boundaries were assumed to be adiabatic; 2) the enclosure was filled with air with Pr = 0.71 and all thermophysical properties (e.g. *specific heat capacity, thermal conductivity*) of the fluid were assumed to be constant [40, 42, 44], except for the fluid density and viscosity, which vary with temperature. For the condition commonly encountered in buildings, the flows in the gas cavity and cells formed between neighbouring PS-TIM slats that sit within it remain laminar, because the *Grashof Numbers (Gr)* never reach the related critical value [41]. Radiative heat transfer was determined using the *Surface to Surface* (S2S) radiation model in FLUENT.

In order to account for the boundary layer effect, the mesh size was defined as smaller near the boundaries and the slats (0.025 mm × 0.025 mm), and then gradually increased toward the centre of the air cavity. Extensive mesh independence studies were undertaken, with these settings, and iterative convergence was assumed to be achieved when the normalized residuals were less than 10^{-3} for the continuity, and 10^{-7} for the energy and momentum equations. More details may be obtained in the authors' previous publication [12]. The simulation was run with a given combination of glazing pane temperatures (which determined the temperature gradient across the glazing unit) and mean glazing unit temperature. The estimated results of local convective heat flux and combined convective and radiative heat flux were calculated from the converged temperature field, from which the thermal conductivity of the PS-TIM layer was determined.

This process was repeated for representative combinations of temperature gradient and mean temperature and polynomial regression of the resulting conductivities was used to determine the equivalent dynamic thermal conductivity of the PS-TIM layer.

$$k_{PS-TIM} = a + bt_m + c\Delta + dt_m\Delta t + e\Delta t^2 + ft_m^2 \quad (5)$$

The constants for the fits made with 10 mm, 7.5 mm and 5 mm pitch PS-TIMs (labelled as '10 mm PS-TIM', '7.5 mm PS-TIM' and '5 mm PS-TIM' respectively in preceding discussions) are given in Table 1.

Table 1: Coefficients for the polynomial regression predicting equivalent thermal conductivities of different PS-TIM configurations for Equation (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	$1\ \text{x}10^{-6}$

The polynomial may be used in EnergyPlus to represent PS-TIM glazing units by using the 'Energy Management System' (EMS) function. This will generate initial estimates of t_m and Δt and then update these within the simulation time step until the solution converges.

2.3 Optical modelling

This section describes how RADIANCE may be used to predict the daylight performance of a space employing a complex glazing system.

2.3.1 Daylight modelling in building performance simulation using RADIANCE

Daylight distribution in a space may be modelled using RADIANCE, which employs backward ray-tracing method. For a space illuminated via a complex fenestration system, such as PS-TIM, only use the total amount of transmitted/reflected flux is not sufficient for an accurate prediction of daylight performance. Representing magnitude and the directional qualities of reflected or transmitted flux, especially the multiple inter-reflections that occur within the system present a challenge for a dynamic annual simulation. Swapping these complex interactions with a pre-calculated transmission matrix (T), which may be expressed by a *Bidirectional Scattering Distribution Function* (*BSDF)* as explained in section 2.3.2, provides an effective description of complex fenestration systems allowing them to be represented in RADIANCE [45]. In addition to the transmission matrix (T), a daylight matrix (D) and a view matrix (V), which describe the external and internal conditions respectively, should also be calculated using a modified daylight coefficient method in advance of annual daylight simulation [46]. 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 [45-47]. 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:

$$i=VTDs \tag{6}$$
$$I=VTDS \tag{7}$$

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.

In this research, the daylight matrix, (D), and view matrix, (V), are obtained based on the model's orientation, surrounding environment, geometry and surface properties of the indoor space using embedded commands in RADIANCE. Sky matrices were obtained from EnergyPlus weather files (in *.epw format) and this paper presents result based on the file for London.

2.3.2 Bidirectional optical properties acquiring method (ray-tracing)

Using BSDFs for characterising complex glazing systems allows them to be represented with precision in daylight and thermal simulations. The BSDF comprises a matrix of coefficients that for light from any given incident direction quantifies the proportion transmitted in all outgoing directions. The use of this approach to represent complex glazing systems has been validated and proven to overcome the limitations of the radiosity method [29, 48, 49]. BSDFs may be generated from the geometrical and material properties of a PS-TIMs using the *genBSDF* function within RADIANCE [50]. This sub-divides the space from which light is incident and into which it is transmitted into 145 segments as indicated in Figure 4 (b) [51, 52]. This is formulation proposed by Klems on the basis that each segment approximately represents an equal cosine-weighted solid angle. The resulting 145 x 145 matrices may then be used in RADIANCE to enable daylight simulation and in EnergyPlus to explore thermal behaviour.

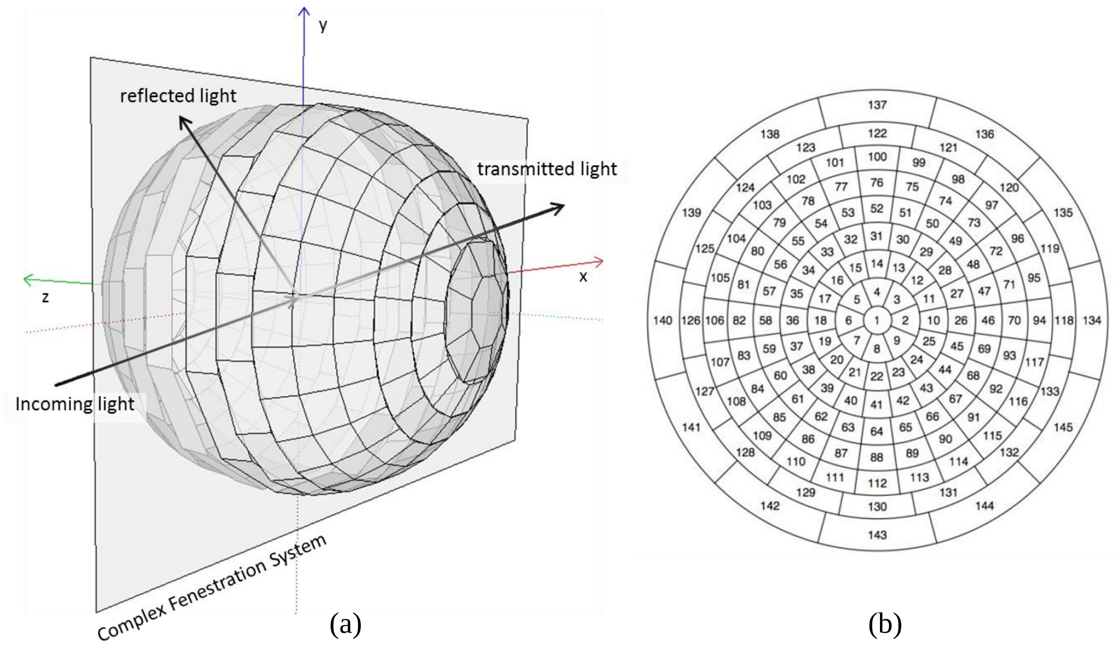


Figure 4: (a) Schematic diagram of *BSDF* for one incident angle and (b) Klems 145-patch hemispherical division of space with numbered subdivisions

3. Integrating PS-TIM into building performance simulation

Use of the workflow shown in Figure 2, to explore the behaviour of PS-TIM was investigated by simulating a single room, based on an office in the Energy Technologies Building, University of Nottingham in the UK.

3.1 Weather data

The study was performed over one hour time steps for an average year using IWEC (International Weather for Energy Calculation) weather file for London (latitude 51.5° N and the longitude 0° W). The diurnal average temperature and direct and diffuse solar radiation taken from the weather file are presented in Figure 5.

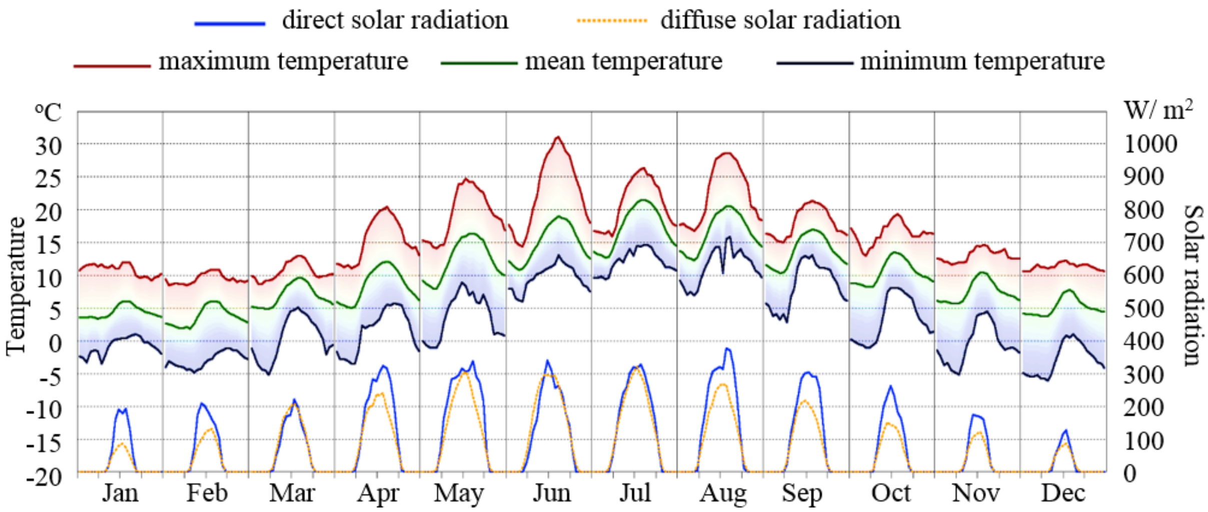


Figure 5: The diurnal average temperature and direct and diffuse solar radiation for London

3.2 Prototype office geometry and modelling

The office glazing was assumed to be south facing and the room considered as part of a larger building where only the south wall is exposed to external conditions. The remaining surfaces of the room were assumed to be buffered by mechanically conditioned spaces and therefore experience no heat gain or loss. Surrounding buildings, vegetation or other obstructions were not considered in this model. The geometry and settings in building simulation of the prototype office are shown in Figure 6 and Table 2.

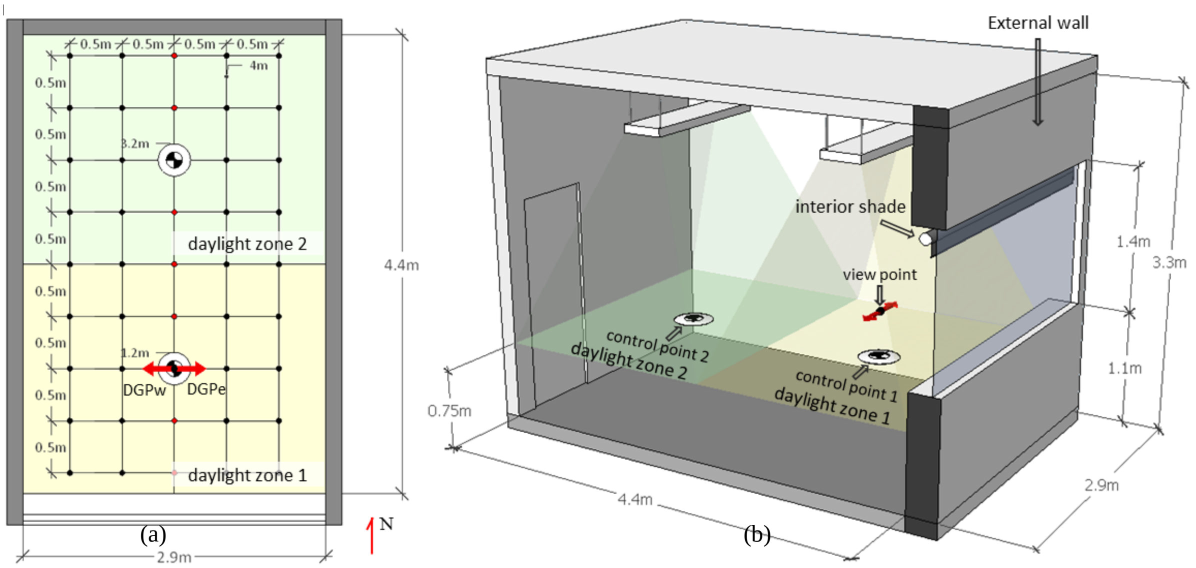


Figure 6: (a) Plan view and (b) section view of the simulated office room

Table 2: Settings for building simulation:

General information	
Orientation	south
Office demissions (m)	2.9 (width) × 4.4 (depth) × 3.3(height)
Window demissions (m)	1.4 (height) × 2.9 (width)
Window height above the floor (m)	1.1
Window to wall ratio	0.42
Number of occupants	2
Number of daylight zone	2
Height of working plane (m)	0.75
Occupancy hours	8:00 – 17:00
Settings used in RADIANCE simulation	
Visible reflectance of floor (%)	30
Visible reflectance of wall (%)	80
Visible reflectance of ceiling (%)	80
Visible transmission of double glazed window (%)	78
Number of daylight calculation points	45
Number of view point	1
Height of view point (m)	1.2
View direction	east and west
Settings used in EnergyPlus simulations	
U-value of exterior wall (W/m^2K)	0.43
Equipment load (W/m^2)	13
Lighting load (W/m^2)	16
Number of lighting control points	2
Illuminance set point for artificial lighting (lux)	500
Temperature setpoint for HVAC system (°C)	21

3.3 Modelling of building daylight simulation

Three-Phase-Method in RADIANCE [53], which is based on hourly daylight weather data, was used for annual dynamic simulation of the luminous environment within the office. As shown in Figure 6 (a) and Table 2, a total of 45 calculation points arranged in a grid over the working plane were used in the model to determine the illuminance distribution. The room was assumed to be used by two people, with one positioned near the window and the second at the back of the room. In order to evaluate the glare, only the occupant position near window was considered.

Within this daylight study, the rendering parameters for RADIANCE presented in Table 3 were used.

Table 3: 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 [36, 47], these settings seem to deliver reliable values for the given scenes.

Daylight autonomy was quantified using *useful daylight illuminance* (*UDI*), which is based on investigations of occupant response to varying daylight illumination [9, 34]. This metric adopts lower and upper thresholds to divide the illuminance level during the working hours of a year into three bins: an *undersupply* bin ($UDI_{<100\ lux}$), which suggests that the daylight illuminances are insufficient as a sole source of light; an *oversupply* bin ($UDI_{>2000\ lux}$), which indicates that the daylight illuminances are very likely to lead to visual and/or thermal discomfort; and a *useful* bin ($UDI_{100\text{-}2000\ lux}$), which is considered to provide useful levels of illuminance. Illuminance *uniformity ratio (UR)* and *daylight glare probability* (*DGP*) were used as metrics to evaluate the daylight comfort level of the indoor space. *Uniformity* *ratio (UR)* is the ratio between maximum and minimum illuminance inside a space [54]. CIBSE [55] recommends that uniformity should not exceed 1:5 for a naturally lit space and the BREEAM [56] assessment method specifies the daylight ratio between average illuminance of a given task area and its immediate surrounds of 1:2.5. Considering both compulsory standard and advanced rating system, the thresholds of UR in this research has been set from 1.5 to 4.5 with an interval of 1. *DGP*, which was introduced and validated by Wienold and Christofferen [57], is the selected metric for assessing discomfort glare. A quick and simplified calculation method to obtain *DGP* over a period of a year is based on the vertical illuminance at the observer (E_v) during each time-step through the following equation [36, 57]:

$$DGP = 6.22 \times 10^{-5} E_v + 0.184 \tag{8}$$

Thresholds of 0.35, 0.40 and 0.45 can be used to divide the DGP results calculated for occupied hours of a year into four bins: lower than 0.35 is 'imperceptible' glare sensation, between 0.35 and 0.40 is 'perceptible' between 0.40 and 0.45 is 'disturbing', while higher than 0.45 is deemed 'intolerable' [35, 36, 57].

3.4 Inclusion of PS-TIM in building energy simulation

As shown in Figure 6 and Table 2, the room is divided into two daylighting zones with two control sensors located at the centre of each daylighting zone at a height of working plane. The daylight illuminance level at these two sensors determines the switching on/off of two lights for these two halves of the room. The HVAC was assumed to be a unitary system with direct expansion cooling and gas heating. To simplify the analysis, a single comfort set point temperature of 21 °C was used all year round. Two scenarios of HVAC operation were applied: one that assumed the HVAC only operates during occupancy hours and a second that that assumed the HVAC is on throughout the year.

In practise, if the occupants in an office are subject to direct sunlight, they are likely to respond by lowering an interior shade or blind. To represent this, thresholds for the horizontal daylight illuminance level on working plane, *(E)*, and a threshold for the *daylight glare probability (DGP)* were set. When the *DGP* at the east or west facing view points, or the illuminance level at point 1, *(E_1)*, exceeded 0.35 or 2000 Lux, respectively [36, 58], an interior shade was assumed to control the daylight and the artificial lighting was assumed to be the main source of illumination. Hourly *DGP* and E_1 data were calculated using RADIANCE and these were then used to generate a schedule in EnergyPlus to control the shading device. This was assumed to have a reflectance of 0.5 and transmittance of 0.1, representing a typical medium reflective and low transparency shading device.

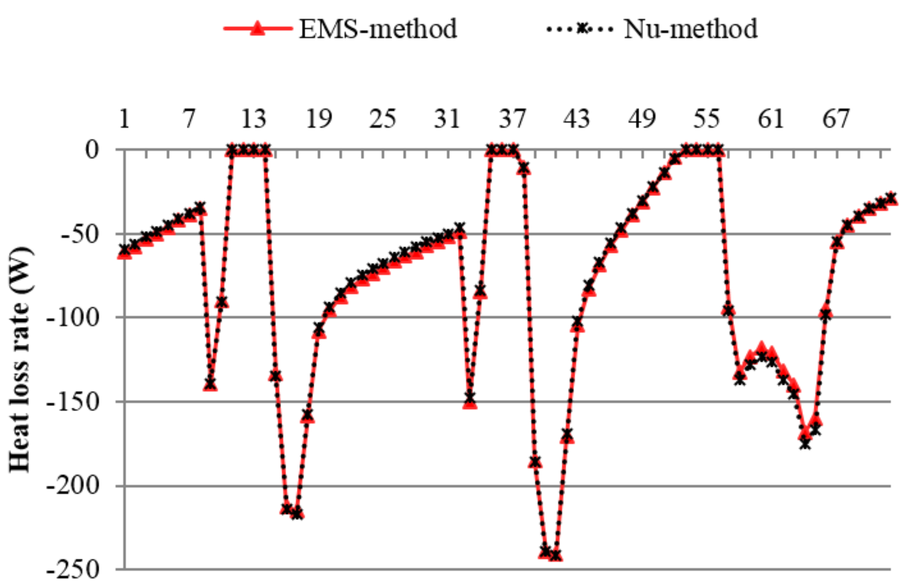
3.5 Importing thermal and optical characteristics of PS-TIM into EnergyPlus

The optical properties of the glazing systems investigated, which were obtained using the genBSDF utility within RADIANCE, were imported into EnergyPlus using the utility, WINDOW. This generates a unified file of the complete system that contains the effects of both the PS-TIM and glazing layers [29], and replaces the traditional radiosity optical model.

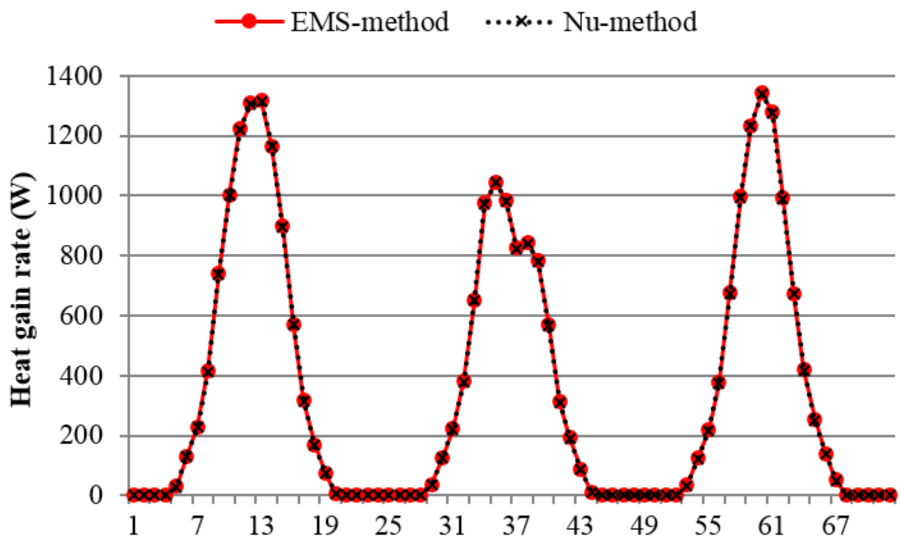
The dynamic thermal properties of the PS-TIM, which were calculated under various temperature conditions using CFD, are in the form of a polynomial describing a series of equivalent thermal conductivities. The polynomial describing the dynamic equivalent thermal conductivities of the glazing integrated PS-TIMs at different slat pitches (i.e. 10 mm, 7.5 mm and 5 mm) were input into EnergyPlus using its built-in ‘Energy Management System’ (EMS) function. This was fed with data from two virtual temperature sensors – one positioned on each surface of each glazing pane facing into the cavity. Based on the detected window surface temperatures, a corresponding thermal conductivity was selected from the dataset in EMS at the beginning of each time-step in the building simulation [59].

3.6 Model verification

EnergyPlus contains a default model for multi-pane windows that estimates the thermal conductivity of the gas layer based on *Nusselt number* (Nu) [27, 39]. This was used to generate heat gain/loss data for comparison with results obtained for a standard double glazing unit using a CFD generated polynomial accessed by EnergyPlus using EMS. Figure 7 shows heat losses through window for the coldest 3 day period in winter and the heat gains through window for the warmest 3 days in summer. It can be seen that there is no significant difference in the heat flows obtained using these two methods. The annual total heating load from the EMS and Nu methods are 51.95 kWh/m^2·yr and 52.71 kWh/m^2·yr, respectively and the cooling loads are 56.05 kWh/m^2·yr and 55.50 kWh/m^2·yr, respectively. The deviation is less than 2% in each case. The comparison between these two methods provides a degree of confidence in the EMS method to represent glazing integrated PS-TIM.



(a)



(b)

Figure 7: (a) Window heat loss under cold weather conditions—3 coldest days; (b) window heat gain under hot weather conditions—3 hottest days. ***In these plots, EMS-method relates to predictions made using the EMS function in EnergyPlus and Nu-method relates to predictions made using the default Nusselt number method in EnergyPlus*****.**

4. Building simulation results and discussion

4.1 Optical performance of the PS-TIM

Detailed daylight predictions for the double glazing unit with and without PS-TIM obtained using RADIANCE were used to explore its effects on daylight availability and daylight comfort. The predicted illuminances during working hours were analysed using *useful daylight illuminance (UDI)*, *daylight glare probability (DGP)* and illuminance *uniformity ratio (UR)*.

4.1.1 Daylight availability after applying PS-TIM

Useful daylight illuminance (*UDI*) was used to evaluate daylight availability for the glazing system with and without integrated PS-TIMs. Figure 8 shows the predicted *UDI* along the central line of the office between the window to the end wall. The blue, green and red lines represent *undersupply UDI*, *useful UDI* and *oversupply UDI* conditions, respectively. Overall, when a normal double glazed window is used (DG on Figure 8), periods when the illuminance exceeds 2000 lux account for over 50% hours of the year for the zone next to the window. This gradually reduces for points further from the window. The use of 5 mm PS-TIM can eliminate the oversupply of daylight, however in so doing, the *undersupplied* daylight hours increase from less than 10% when the original DG is used to more than 20%. The percentage of hours where the *UDI* is in the *useful* range increase from 30% for the conventional DG to 68% for the 10mm PS-TIM and rise to 80 % for the PS-TIMs with 7.5 mm and 5 mm slat pitches. The data in the *useful* range also imply that the daylight is relatively evenly distributed throughout the room, especially for the PS-TIMs with slat pitches of 7.5 mm and 5 mm. Thus, the integration of PS-TIM improves the daylighting quality of the room, especially within the region next to the window where over illumination is frequently a problem with conventional glazing.

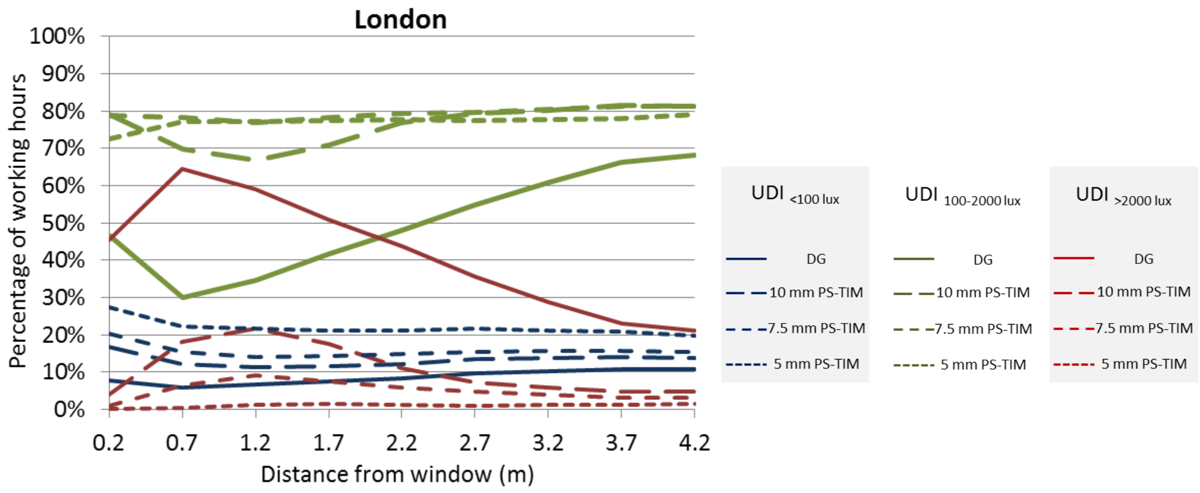


Figure 8: UDI distribution in the office with glazing integrated PS-TIM

4.1.2 Daylight comfort after applying PS-TIM

Figure 9 (a) shows the uniformity inside the office derived from the 45 daylight study points. When the original DG is used, the natural daylight transmitted to the room results in sharp contrasts, between a strongly illuminated area close to the window and the remainder of the room. For 42% of the working hours during the year, the room has a *UR* larger than 1:4.5 and a further 47% of hours have a ratio in the range of 1:3.5 ~ 1:4.5, indicating that for over 90% of this period, uniformity significantly exceeds the recommended BREEAM maximum thershold of 1:2.5 for daylighting good practice. The integration of PS-TIM effectively improves the daylight uniformity. The hours with *UR* exceeding 1:2.5 have been reduced from 97% to 15%, 10% and 4% by applying 10 mm, 7.5 mm and 5 mm PS-TIM, respectively.

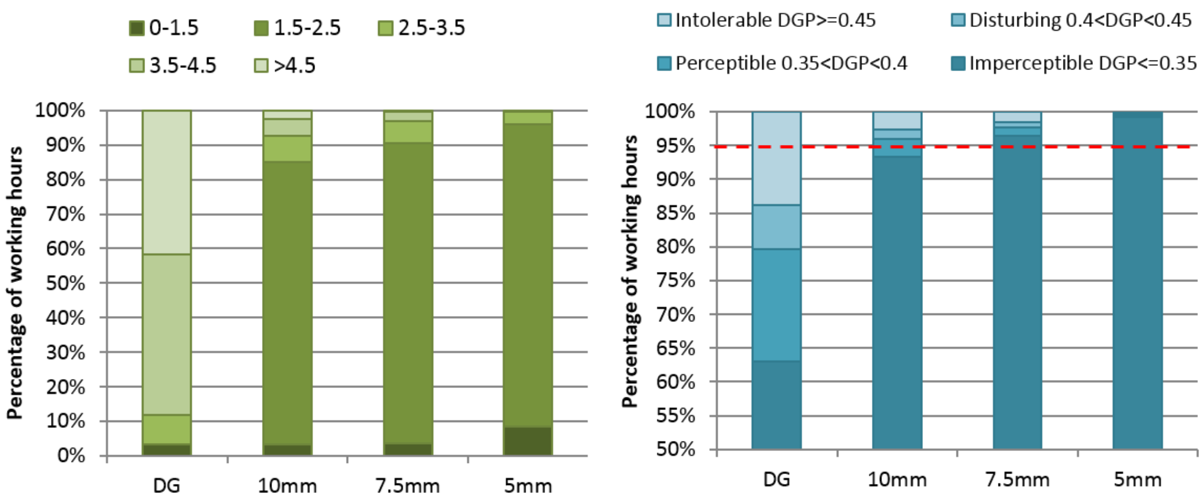


Figure 9: (a) Uniformity for glazing with and without PS-TIM, (b) *DGP* for glazing with and without PS-TIM.

The results of *Daylight glare probability* (*DGP)* for the double glazing with and without PS-TIM are shown in Figure 9 (b). For the original double glazed window, intolerable glare (*DGP* ≥ 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 occupied hours, respectively. When diffuse translucent PS-TIM structures were applied, significant improvement of the percentage of *imperceptible* glare (*DGP* ≤ 0.35) is achieved. The figure increases from 63.1% of working hours for DG to 93.4%, 96.5% and 99.2% with the application of PS-TIM with slat pitches of 10 mm, 7.5 mm and 5 mm, respectively. According to the Wienold's criteria [36] for categorising glare conditions in a room, when the 7.5 mm 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 for over 95% of office working hours the glare is *perceptible*. These luminous environment quality simulations were carried out independently of the energy simulation and so do not include the contribution made by artificial lighting and use of shading described in the next section.

4.1.3 Requirement for interior shading to prevent strong daylight

In practice, if the occupants in a working space are disrupted by high illuminance levels or glare from the windows, they are likely deploy interior shading devices if they are present. This would significantly reduce the availability of daylight, and hence result in the illuminance level deeper within the space becoming insufficient for work. Consequently, artificial lighting is required.

PS-TIMs have been integrated into double glazing to reduce the probability of using interior blinds. Figure 10 shows the average hours per week when shading is deployed on two thresholds (i.e. illuminance level >2000 lux and *DGP>0.35*). During the 45 working hours per week, the average hours when shading is used reduce from 34.3 hours for the space illuminated via DG to 6.5 hours for a glazing unit with 10 mm PS-TIM. Integration of 5 mm PS-TIM can nearly eliminate the requirement for interior shading.

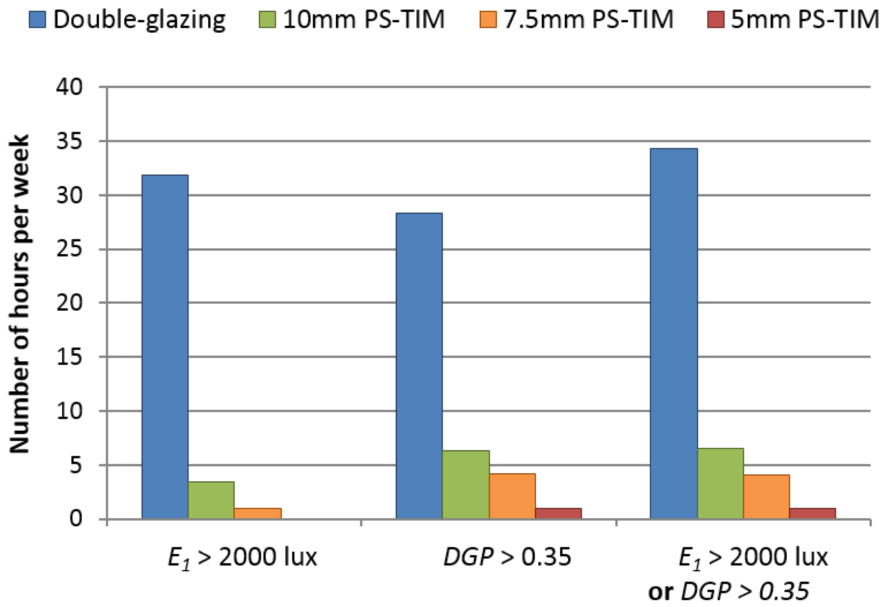


Figure 10: Average number of hours per working week when discomfort daylight conditions exist. Simulation performed using London EPW data

4.2 Total energy consumption after applying PS-TIM

This section presents the annual energy consumption of the office for the different glazing configurations. The energy consumption is expressed in terms of kWh/m^2 per year and they are further divided into heating, cooling and lighting energy consumption. For the purpose of predicting the potential energy saving resulting from the use of PS-TIMs, the energy consumption using a conventional double gazed window with and without an interior shading are also calculated for comparison. Two HVAC scenarios were investigated: a scenario where the HVAC operates during working hours from 8:00 to 17:00 on weekdays and a scenario where the HVAC operates continually throughout the year.

As shown in Figure 11, the 10 mm PS-TIM provides the best overall energy efficiency for the assumed HVAC operation schedule of working hours during weekdays.

Compared with the conventional double gazed window with interior shading, an overall energy reduction of 15.5% can be achieved under the selected London climate. Most of the energy reduction occurs in lighting and cooling. Adoption of the 10 mm PS-TIM delivered lighting energy savings of 25.7%, a cooling energy saving of 24.6%, and a more modest 2.4% heating energy saving. This can be explained by the hourly window heat gain, heat loss and the space heating energy consumption for the window with and without 10 mm PS-TIM during a typical 48 hours period in winter as shown in Figure 12. Day 1 represented an overcast day without obvious solar heat gain and day 2 represented a clear sky condition with plenty of passive solar heat gain. Although, the presence of PS-TIM increases the thermal resistance of the window system, and hence reduces the heat loss, it simultaneously reduces the solar heat gain that is transmitted through the window and warms up the office during the daytime (Figure 12 (a)). In winter, these work against each other and the balance results in only a modest reduction in heating energy consumption. Therefore, when the HVAC system operates during working hours only, the heating energy consumption for the office with a window system with a better thermal resistance provided by PS-TIM dose not result in a significant total energy reduction.

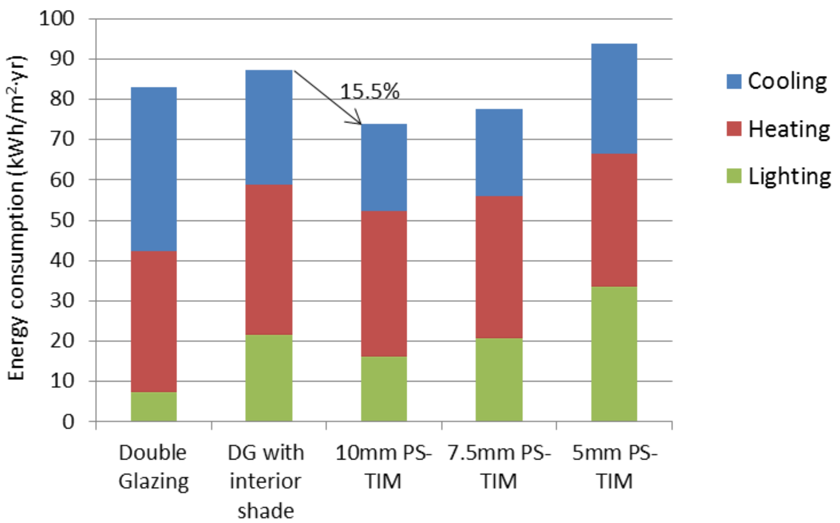
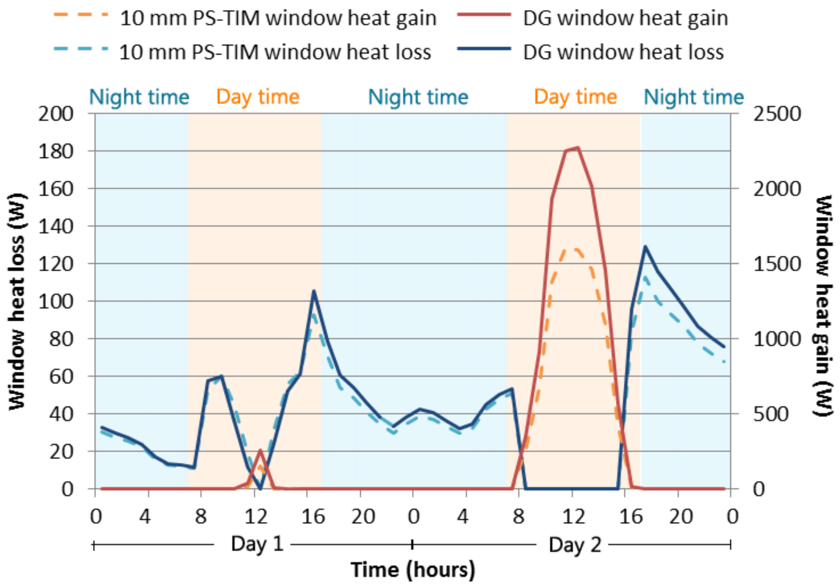
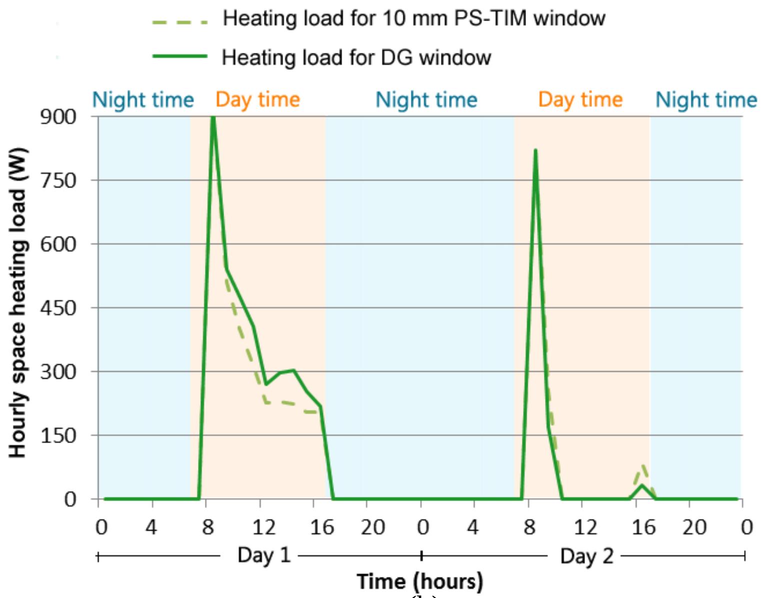


Figure 11: Annual heating, cooling and lighting energy consumption when HVAC operates between 9:00-17:00 on workdays. Simulation performed using London EPW data.



(a)



(b)

Figure 12: (a) Hourly window heat gain, heat loss and (b) hourly space heating loads for a window with and without PS-TIM when HVAC operates between 9:00-17:00 on workdays. Simulation performed using London EPW data.

The benefits of integrating PS-TIM into glazing systems grows significantly if it is assumed the HVAC operates continually through the year. As may be seen from Figure 13, 7.5 mm PS-TIM provides best energy saving potential. The heating demand is dramatically reduced by 30.9% lighting energy savings of 31.2% are achieved and a cooling energy drops by 42.8%. The reason for the improved performance especially for the PS-TIM with smaller interval distance (i.e. 7.5mm and 5 mm) is that while the issue of reduced solar gains is still present during daylight hours, the improved thermal resistance results in a dramatic reduction of heating energy demand during the night time as illustrated in Figure 14.

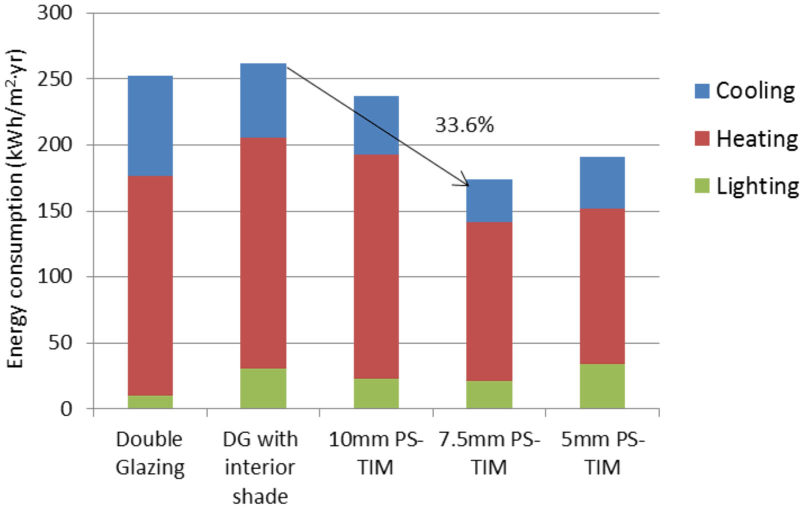
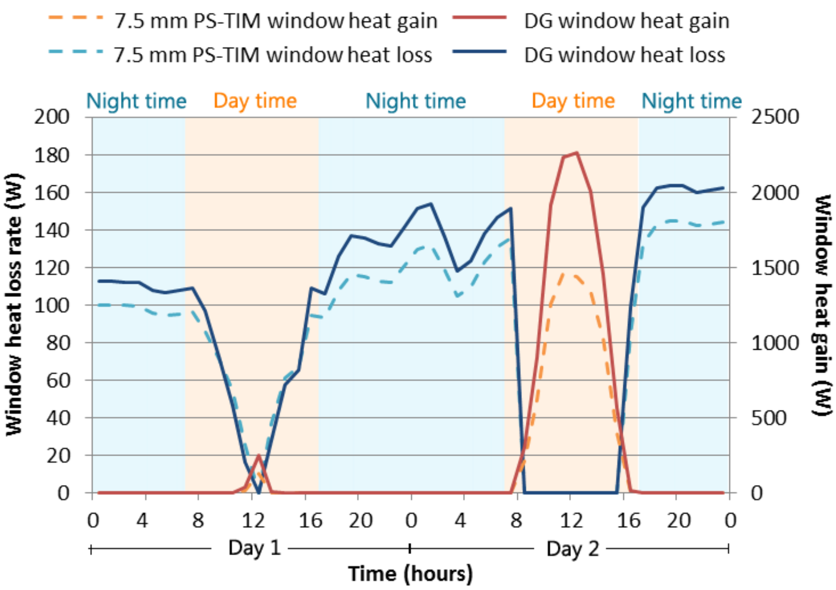
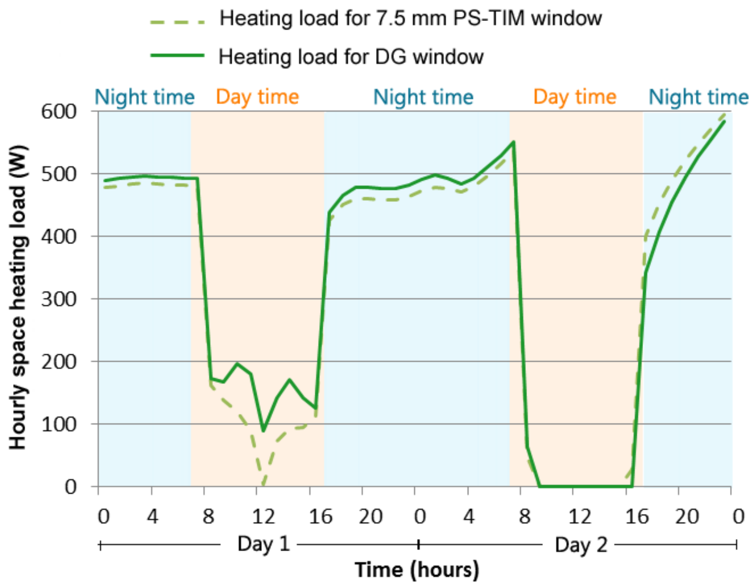


Figure 13: Annual heating, cooling and lighting energy consumption when HVAC operates continually. Simulation performed using London EPW data.



(a)



(b)

Figure 14: (a) Hourly window heat gain, heat loss and (b) hourly space heating energy consumption of applying window system with and without PS-TIM when HVAC operates continually. Simulation performed using London EPW data.

The analysis of energy consumption under these two HVAC operation scenarios illustrates how the proposed work flow may be employed to offer a quantitative assessment of the effect of varying thermal and optical properties of building glazing through the integration of PS-TIMs.

5. Conclusion

A good glazing system needs to simultaneously solve the problems of visual discomfort and energy inefficiency that are evident when conventional double glazed window systems are used. This research developed a comprehensive workflow for simulating the performance of spaces served by complex glazing systems, which was then used to investigate the thermal and optical performance of a window system with Parallel Slat Transparent Insulation Material (PS-TIM) and its impact on building performance. In this model, EnergyPlus has been combined with a thermal model developed using Computational Fluid Dynamics and an optical model developed using a ray-tracing technique to predict the impact of PS-TIM on building heating, lighting and cooling energy consumption. RADIANCE has been used to predict detailed daylight performance of a space served by windows with integrated PS-TIM. Based on the application of this workflow to explore the performance of a small office space served by a glazing integrated PS-TIM window, the following conclusions can be drawn:

1) The workflow for predicting building daylight and energy performance has been verified and has the potential to provide a detailed prediction of performance.

2) The integration of PS-TIM improves the luminous environment within the space it serves, especially within the region that is close to the window where over illumination, which is frequently a problem with conventional glazing, is controlled and glare is virtually eliminated.

3) When compared with a conventional double glazed window combined with an interior shade to counter over illumination and glare, applying PS-TIM in London (as represented by an EPW weather file) can provide up to 15.5 % energy reduction when HVAC

operates during working hours and up to 33.6 % energy reduction when HVAC operated continually.

This study has not explored the impact of using PS-TIM on view either out of or into space served by PS-TIM, and this represents a limitation that requires further study. However, the workflow that combines the outputs from CFD and optical modelling tools and integrates these into EnergyPlus to provide a holistic energy simulation of spaces served by glazing integrated PS-TIM is a new development. This offers a first step in developing design strategies that seek to balance view considerations with the improvements in thermal and luminous environment of spaces served by glazing integrated PS-TIM systems.

Acknowledgements

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