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IMPACT OF INTERNAL SHADING CONTROLS ON EFFICIENT DAYLIGHTING IN HOME-OFFICE WORKSPACES IN TROPICAL CLIMATES

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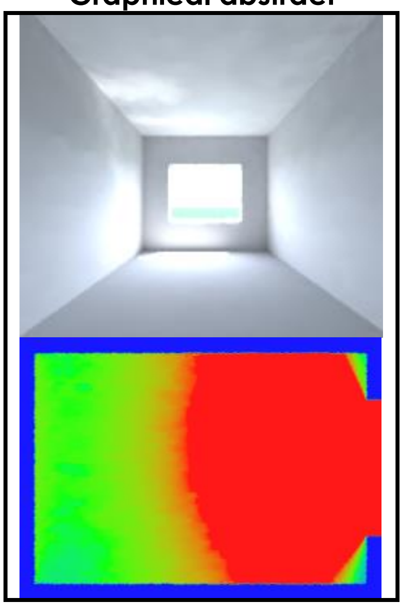
Graphical abstract



Abstract

Home office workspaces have significantly grown in residential sectors throughout the world. Nowadays, many people worldwide are forced to work from their housing units due to the outbreak of the COVID-19 pandemic. However, the existing residential buildings were only designed for living activities, not for desk-related tasks. This is more critical in tropical regions with the overabundance of indoor daylight and lack of external shadings on existing buildings. Despite the limitations for modifying the external facades, interior retrofit plays a major role in improving visual environments. Daylighting performances of various configurations, including internal shading devices, interior surfaces, and window films, were experimented with the Radiance-IES program. A field measurement of daylight was conducted in a home office room under the Malaysian tropical sky to validate the simulated results. This research proved that the existing residential buildings in the tropical climates had poor daylighting performance where the mean indoor illuminance could be over 10,000 lx. The combination of a light shelf, a partial blind, and the tinted window film could effectively 85% alleviate the excessive indoor daylight level. This configuration recorded a significant improvement in Useful Daylight Zone (around 300%), and Daylight Glare Probability was considerably reduced from 0.46 to 0.34.

Keywords: Daylighting, internal shading, tropical climate, home office, COVID-19

1.0 INTRODUCTION

Due to the fast development of computer services and Internet capabilities, many people have relocated their offices to their homes [1,2]. This has several advantages for home office users, such as increasing flexibility, productivity, and independence while working, saving their money and time, decreasing human and vehicular traffic, facilities cost, and daily commuting [3–6]. Home office with different types of desk-related tasks such as computer work and paperwork may exclusively occupy a whole room or may be located in other places in a residential unit while a spare bedroom is often utilised for home office workspaces [4]. Home offices have considerably increased worldwide. A survey in several high-rise residential buildings in Malaysia showed that most occupants carried out at least a type of desk-related tasks in their residential units during the daytime [7]. The current outbreak of coronavirus disease (COVID-19) all over the world has obliged people to work from their homes, especially those people who are performing any type of desk-related tasks. Nevertheless, the existing residential buildings have been mostly designed for accommodation purposes but not for office tasks in which providing visual comfort is essential for such users.

Daylighting is more beneficial than electric lighting for equal amounts of light since it creates lower heat gain and better quality [8]. In addition to energy savings in buildings, efficient daylighting strategies can considerably provide healthy indoor environments and visual comfort for residents [9–12]. Wong and Istiadji [13] declared that daylighting design has been the major issue in residential sectors to provide healthy and energy-efficient buildings in tropical climates. Kanarek [4] indicated that daylighting is essential in home office workspaces to prevent eyestrain, irritability, and to enhance the quality of visual environments. Recent research highlighted the importance of daylighting strategies during the fatal COVID-19 pandemic in residential buildings, especially in the mornings [14].

Malaysia, with the latitude of 1°N to 6°45´N and the longitude of 99°36´E to 104°24´E, locates in the tropical region with high solar radiation, dynamic cloud formation, and excessively great outdoor illuminance [15,16]. However, the abundance of daylight is not utilized in many existing buildings in the tropical climate. This is even more critical for unobstructed buildings without shading devices or well-designed shading controls on their external facades resulted in direct penetration of tropical sunlight into such buildings. A survey was conducted by the authors in several home office buildings with no external shadings on their facades in the Malaysian tropical region [7]. Due to glare problems and excessive indoor sunlight levels, most home office users overuse internal shadings such as curtains or blinds. Besides, the users switch on electric lighting to carry out their desk-related tasks despite high daylight availability in those buildings. This causes an increase in energy consumption and results in low productivity and fatigue for the home office users. Another research in a tropical climate by Jamaludin *et al*., [17] showed that many users in the residential college buildings reject natural lighting, during the daytime, while they use electric lighting instead. In tropical regions, residents typically use an air conditioner and electric lighting to overcome the heat gain from inefficient daylighting in their residential units [18].

Architects have realized the benefits of daylighting since the 1990s and started to integrate daylight into many new building designs [19]. Previous research in tropical climates was also mostly focused on daylighting strategies for designing new buildings, such as orientation [20, 21], building form [22], window geometry [23], [24], external shading devices [25]. However, applying these techniques in existing buildings may be infeasible or uneconomical, as mentioned by Mayhoub and Carter [26]. In comparison with new buildings, existing buildings have more limitations in employing energy-efficient strategies. Thus, retrofitting can be the only solution to enhance indoor daylight efficiency when a building already exists. While many existing residential buildings were not designed for daylighting, interior retrofit approaches could be essential for daylighting design in such buildings. Maier [27] proved that successful retrofitting strategies for daylighting in residential buildings would decrease energy consumption, provide an appealing environment and financial profits, and significantly influence climate changes.

Numerous daylighting studies in tropical regions were frequently conducted in commercial or office buildings. Compared to new buildings, there is not enough investigation about daylighting design for existing home office buildings, particularly in the tropical contexts. This paper deals with various interior design parameters to retrofit the home office workspaces, in the existing residential buildings, for efficient tropical daylighting. Different types of internal shading devices, surface reflectivity, and window films were investigated to maximize the efficiency of tropical daylighting and to minimize the extremely high daylight levels in home office workspaces. Residential buildings in this paper referred to those unobstructed apartment buildings, irrespective of their heights, which were not blocked by adjacent buildings for access to sunlight.

2.0 METHODOLOGY

This paper employed the Radiance tool through Integrated Environmental Solution Virtual Environment (IES-VE) software to investigate daylighting performances of various interior layouts. IES-VE, as a multifunctional simulation software, can analyze energy efficiency in buildings from the preliminary stages of design [28]. The Radiance-IES simulation engine generates high-quality daylight modelling images compared to other daylight simulation tools [29]. Several researchers showed that the International Commission on Illumination (CIE) sky models, used by most of the simulation software, especially Radiance-IES, are distinct from tropical skies [30–34]. As a combination of various daylighting techniques could help scholars to validate simulation findings, a field measurement of daylight was conducted to show discrepancies between the simulated results, derived from the Radiance-IES software, and the measured results under different Malaysian tropical skies.

2.1 Validation Test

A test room with a single aperture, located in Universiti Teknologi Malaysia (UTM), Johor, (1.5592°N and 103.6414° E), was employed for empirical validation of the simulation tool (Figure 1). Three Lux meters (Delta-OHM-LP-471-PHOT) with the data loggers (Photo-Radiometer Delta-OHM-HD-2012.2), Probes P_1, P_2, and P_3 as shown in Figure 2, were positioned at the work plane height (75 cm) in the room to calculate the work plane illuminance (WPI). Concurrently, a Lux meter (Delta-OHM-LP-PHOT-02) was placed on the building roof, at the height of 1450 cm above ground level, to calculate outdoor illuminance (measurement range: 0-150 Klx). Referring to Nikpour *et al*., [35], a calibration test is essential to evaluate the precision of illuminance meters. Hence all the illuminance meters were calibrated before measuring daylight in the room to check the equipment's accuracy compared with each other.

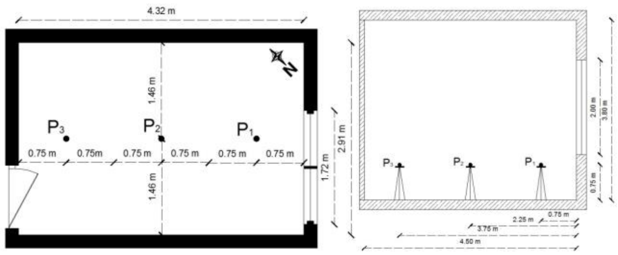


Figure 1 Geometry of the test room for the field measurement: (left) plan; (right) section

Figure 2 Measuring illuminance levels by (left) internal sensors; (right) external sensor

Equation (1) illustrates the method of measuring surface reflectance [36], where L is luminance ($cd.m^{-2}$), E is illuminance (lx), and ρ represents surface reflectance. As depicted in Figure 3, the luminance values of interior surfaces in the test room were measured by a luminance meter (LP-471-LUM-2) with a measurement range of 0.1 $cd.m^{-2}$ to 2×10^6 $cd.m^{-2}$. The illuminance values were measured by a digital Lux meter (TES-1332A). Table 1 shows the reflectance values of the interior surfaces in the test room.

$$\rho = L\pi / E \quad (1)$$

Figure 3 Calculation of the surfaces' reflectance through measuring: (left) luminance; (right) illuminance

Table 1 Interior surfaces' reflectance in the test room

Surfaces	Reflectance (%)
Ceiling	88
Walls	74
Floor	10
Door	23

The field measurement was conducted in the test room during 8-11 March 2019 to calculate daylight levels from 9:00 a.m. to 6:00 p.m. under different tropical skies (intermediate and overcast). Subsequently, the test room was modelled by the Model IT tool in IES-VE with the identical geometry and the surfaces' reflectance. Sky conditions, dates, and times of the simulation tests were adjusted based on the real measurement. Previous studies proved that relative ratios are more accurate for daylight simulation under the tropical skies than absolute values [30,32]. Thus, instead of using absolute illuminance values, daylight ratio (DR) for the intermediate skies and daylight factor (DF) for the overcast skies were used to calculate daylight levels in the test room (Equation 2). Figure 4 illustrates the measured and simulated DR and DF on average for the 4-day experiments in the test room. Both measured and simulated results followed almost similar patterns by neglecting the minor differences. In this case, Pearson correlation analysis was employed to represent the relationship between the measured and simulated values, shown in Table 2. Findings of the validation test show that the Radiance-IES program has a strong capability to simulate daylighting performance under tropical skies.

$$\text{DR or DF} = \text{Internal WPI} / \text{Outdoor Illuminance} \times 100\ \% \quad (2)$$

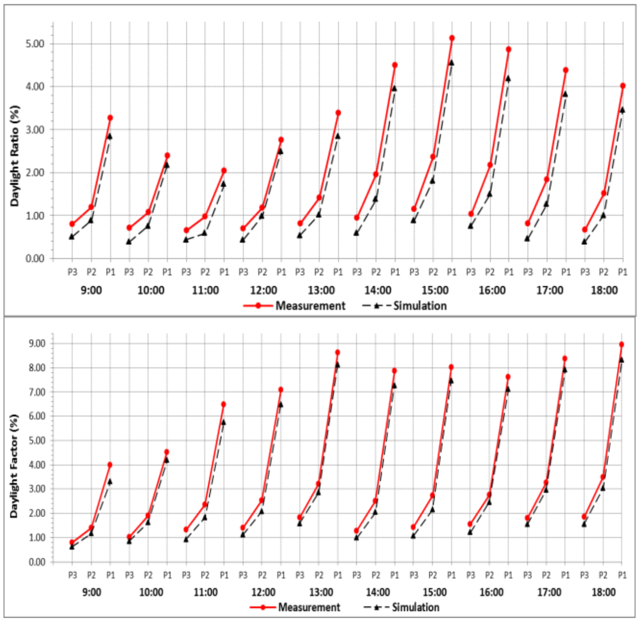


Figure 4 Measured and simulated DF & DR in the test room

Table 2 Pearson correlation analysis of measured and simulated DR and DF in the test room

Relative ratios	N	Sig. (2-tailed)	Pearson Correlation
DR	90	.000	.812**
DF	30	.000	.945**

**. Correlation is significant at the 0.01 level (2-tailed).

2.2 Simulation Procedure

Using the test room was only for the empirical validation of software under tropical skies through the field measurement. However, to have better generalization, the modelled room in simulation experiments was derived from a survey by authors that were conducted in several residential buildings in Malaysia. Hence the modelled room was representative of a typical home office in residential buildings in Malaysia. According to Figure 5, the modelled room is divided into three zones to show daylight levels for different spaces from the window. While every furniture layout may influence daylighting performance in residential buildings [37], it is not practical to generalize furniture arrangements for daylighting studies.

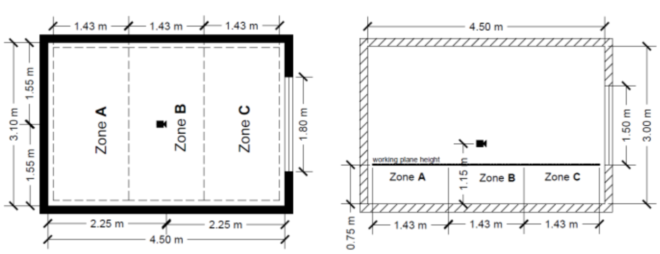


Figure 5 Geometry of the room in simulation experiments: (left) Plan; (right) Section (Camera's height = 115 cm)

The design parameters in this study were chosen from those with a high potential of being implemented in retrofit projects. Although light shelves can be fixed on a window internally or externally, internal light shelves are more flexible and easier to be used by end-users [38]. Wong and Istiadji [13] claimed that an internal light shelf is an appropriate solution to reduce the exposed area of a window and to enhance the reflected light in residential buildings under the tropical climate of Singapore. According to Huff and Huff [39], an internal light shelf as a daylighting strategy can be employed for retrofit applications. Vertical blinds are not beneficial for tropical daylighting in buildings as they worsen indoor daylight uniformity; hence screening daylight horizontally is better than vertically [40]. Venetian blind as a dynamic internal shading has the potentials to obstruct direct sunlight patches and to control daylight penetration into buildings, and it has a significant effect on providing visual comfort for residents [41,42]. Thus, three types of internal shading devices were investigated in this paper; a single light shelf, a partial Venetian blind (located at the upper part of the window), and an integrated light shelf with a partial Venetian blind (located at the lower part of the window).

Window glazing films or solar control films can be generally installed on a window even by the end-users. A window film typically consists of polyester films with a thin layer of tinting materials such as metals, ceramics, carbon, etc., which are placed on the films [43]. Tinted windows have high potentials to control sunlight penetration, glare, and to reduce electric lighting and cooling load of air conditioners in residential buildings [38,44]. In a research by Konis [45], solar control film as an interior retrofit strategy was used to enhance daylighting efficiency and visual comfort in buildings. Jamaludin *et al.*, [46] also declared that tinted window glasses could be widely employed for either retrofit or new residential buildings design in tropical regions. Referring to previous studies, clear and tinted window films are commonly used in residential buildings in tropical regions [20, 47,48]. Window glazing with the visible transmittance (*vt*) of 20% to 80% is mostly used In Malaysia [49,50]. In another study by Lim *et al.*, [51], the visible transmittance of 53% and 54% were used in several existing buildings in Malaysia. Thus, a clear window film with the visible transmittance of 80% and a tinted film with the visible transmittance of 50% were considered in this paper.

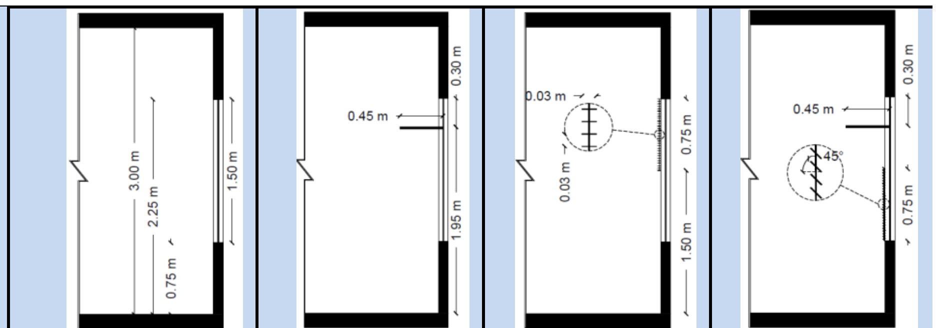
Surface reflectance can influence daylight distribution and glare in buildings [52]. Occupants can change their room's surfaces by painting the interior surfaces or carpeting the floor. Room surfaces have the potential to be considered for daylighting design in retrofit projects [53]. A study by Nasrollahi and Shokry [54] showed that the reflectivity coefficient of 0.4 for floor and 0.6 for walls are more desired for lighting in buildings. Based on the IESNA [55] Standards, the recommended range of reflectance for interior surfaces is 60-90%, 35-60%, and 15-35% for a ceiling, walls, and a floor, respectively. Thus, in this paper, the lower and the upper thresholds of surfaces' reflectance were used to have better generalization. In this case, the two conditions of reflectance values were 90%-60%-35% and 60%-35%-15% (ceiling-walls-floor). Table 3 shows the roughness and specularity of the interior surfaces, taken from the recommendations [55,56].

On the whole, internal shading device, surfaces reflectance, and window film were the independent variables in this study, and their various configurations were considered for the simulation experiments in the modelled room (Table 4). The base configuration shows the existing condition of a typical home office room, without shading controls, in Malaysia. C_{1-3} represent different combinations of the window films and the surfaces' reflectance, excluding shading devices, in the modelled room. In addition to the window films and the surfaces' reflectance, a single light shelf is added for the L_{1-4} configurations. While the B_{1-4} configurations have a partial blind (at the upper part of the window), both light shelf and partial blind (at the lower part of the window) are considered for LB_{1-4} as shown in Table 4.

Table 3 Properties of interior surfaces in the modelled room

Surface	Specularity	Roughness
Ceiling	0.03	0.03
Wall	0.03	0.03
Floor	0.03	0.05
Venetian blind	0.05	0.03
Light shelf	0.05	0.03

Table 4 Geometrical configurations of the sixteen interior parameters in the modelled room



Independent Design Variables		Base	C_1	C_2	C_3	L_1	L_2	L_3	L_4	B_1	B_2	B_3	B_4	LB_1	LB_2	LB_3	LB_4
Internal Shading Device		Without shading (C)				Light shelf (L)				Blind (B)				Light shelf & Blind(LB)			
Window Film (% vt)	Clear (80 %)	*	*	–	–	*	*	–	–	*	*	–	–	*	*	–	–
	Tinted (50 %)	–	–	*	*	–	–	*	*	–	–	*	*	–	–	*	*
Surface Reflectance (Ceiling / Walls / Floor)	Upper Th. (90/60/35)	*	–	*	–	*	–	*	–	*	–	*	–	*	–	*	–
	Lower Th. (60/35/15)	–	*	–	*	–	*	–	*	–	*	–	*	–	*	–	*
Configuration		Base	C_1	C_2	C_3	L_1	L_2	L_3	L_4	B_1	B_2	B_3	B_4	LB_1	LB_2	LB_3	LB_4

As the intermediate sky is the most frequent type of sky in the Malaysian tropical climate (about 86% yearly) [57, 58], this sky model was used for the daylight simulations. Three critical dates of 21 March (equinox), 22 June (summer solstice), and 22 December (winter solstice) were considered for the simulation experiments. These particular dates were selected to represent the most serious climatic conditions of the sun path in the tropical sky of Malaysia. In other words, the highest and the lowest solar altitudes are recorded on the summer and winter solstices, respectively, while the sun's altitude lies between the values of these two solstices on the equinox [50]. To experience different behavior of the sun concerning the room's window, all cardinal orientations (North, South, East, and West), and three critical times during a day (9:00 a.m., 12:00 p.m., and 3:00 p.m.), representing different solar azimuth angles, were employed for the simulation tests.

2.3 Criteria of Analysis

Through the validation test, it was proved that the relative ratios of illuminance such as DR could be used for indoor daylight simulations under the Malaysian tropical skies. While DR shows the availability of daylight illuminance, estimated work plane illuminance (eWPI) demonstrates the usability of indoor daylight illuminance [34, 59]. Equation (3) was employed to calculate indoor illuminance values for the tropical climates [34, 59–61]. Accordingly, eWPI is dependent on DR and also estimated outdoor illuminance which was obtained from the real measured data for the Malaysian tropical skies [57,58,62], and the weather data file (EPW) for Johor Bahru, Malaysia, taken from the online website [63].

$$\text{eWPI} = (\text{DR} / 100) \times \text{Estimated Outdoor}$$

Dynamic daylight metrics such as UDI have been widely used to evaluate daylight efficiency in buildings for different climatic conditions [50, 64–67]. UDI is specified as the yearly occurrence of daylight illuminances in a certain range called "useful" by the users; when daylight illuminance values are in the range of 100-500 lx, it is considered as "UDI-supplementary" [50,67]. Moreover, Dubois [68] claimed that WPI of 100-500 lx is acceptable and ideal for desk-related tasks, while WPI of lower than 100 lx and higher than 500 lx is inappropriate for such tasks. In a study by Mahdavi *et al*., [23], the *Suitable Area Zone* as a daylight index was employed to calculate the percentage of an area in a room with allowable WPI for desk-related tasks. While various activities, in addition to the desk-related tasks, might be performed in a home office room, UDZ (Useful Daylight Zone) in this study referred to the percentage of the room's area with eWPI of 100-500 lx. Accordingly, eWPI of lower than 100 lx, as UDZ fell-short (UDZ-f), indicated the time of insufficient daylight while the illuminance values of over 500 lx showed UDZ exceeded (UDZ-e), which could lead to visual discomfort for home office users (Table 5).

Table 5 Useful daylight zone (UDZ) for the desk-related tasks

eWPI	Description	Symbol
< 100 lx	Lower-limit Zone (UDZ fell-short)	UDZ-f
100 lx – 500 lx	Useful Daylight Zone (UDZ achieved)	UDZ
> 500 lx	Upper-limit Zone (UDZ exceeded)	UDZ-e

In this paper, the most critical time of glare incidence for each orientation in the modelled room was considered to show the differences between the base case and the optimum configurations derived from the results of illuminance analyses (i.e., eWPI and UDZ). Although there are several indices to assess visual comfort for occupants in buildings, each one is applicable for a specific lighting condition [69]. Suk *et al*., [70] claimed that Daylight Glare Probability (DGP) is the most appropriate index to compute absolute glare issues. Jakubiec and Reinhart [71] found that DGP shows the most plausible results than other glare metrics such as Daylight Glare Index or Visual Comfort Probability. In case of direct sunlight incidence in a side-lit room, DGP is more applicable than other existing indices as it can predict a much higher probability of discomfort glare [71]. Therefore, DGP, as the most robust index and the least prone to show incorrect glare predictions, was employed to analyze glare in the modelled room with a high presence of direct sunlight. Glare probability of higher than 0.45 represents an "intolerable" glare, whereas values lower than 0.35 are indicative of an "imperceptible" glare. In addition, DGP values in the range of 0.35-0.40 and 0.40-0.45 are considered "perceptible" and "disturbing", respectively [72,73]. The camera was located at a height of 115cm in the center of the room facing the window to represent the worst glare scenario in the room (Figure 5).

3.0 RESULTS AND DISCUSSION

3.1 eWPI Analysis

Figure 6 illustrates the mean eWPI recorded by all sixteen interior layouts in different room spaces under north orientation. Overall, the base case causes the highest illuminance value among all in the whole room during the studied days. On 21 March in the morning, the mean eWPI is 3,208 lx in zone C where LB_3 and LB_4 could meet the allowable range (100-500 lx) whereas the other configurations exceed this range; from midday onwards, only the LB cases record acceptable illuminance level in zone C. The north-facing room receives the highest sunlight level on 22 June when the mean eWPI is 6,708 lx (at 9 a.m.), 7,339 lx (at noon), and 6,478 lx (at 3 p.m.) by the base case in zone C. Meanwhile, the other layouts represent much higher illuminance than the allowable range. On 22 December, although $LB_{1\text{-}4}$ record acceptable eWPI in zone C during the day, they fail to show potential for allowable daylighting in zone A; in addition to the base case, other layouts record acceptable eWPI in zone B from the morning onwards. On the whole, for north orientation, C_1, $L_{1\text{-}2}$, and $B_{1\text{-}2}$ have allowable illuminance levels in the farthest zone from the window, while $B_{3\text{-}4}$ and $LB_{1\text{-}2}$ show acceptable daylight levels in the middle zone. Moreover, $LB_{3\text{-}4}$ are the best configurations among all in the nearest zone to the window.

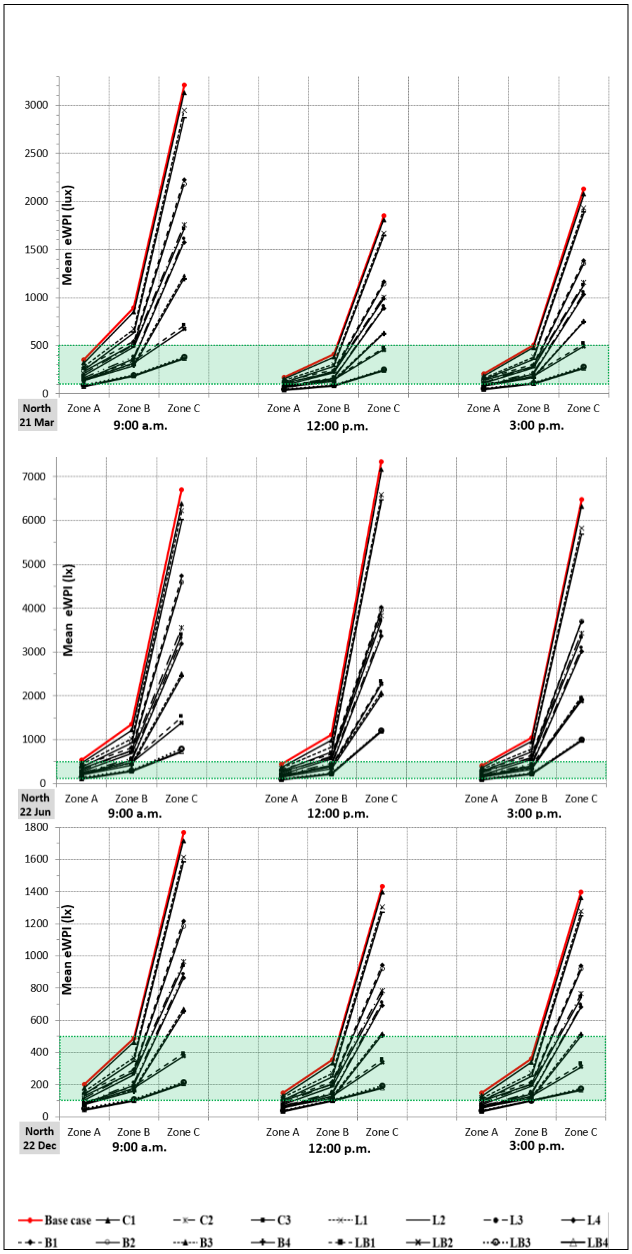


Figure 6 Mean eWPI recorded by 16 configurations in the north-facing room

The most serious sunlight availability in the south-facing room is 22 December when the sun has the lowest altitude in the sky. As shown in Figure 7, the highest eWPI is recorded in zone C by the base configuration with 5,275 lx in the morning, 7,747 lx at noon, and 6,328 lx in the afternoon. On the contrary, LB_4 is the only configuration in zone A with a mean eWPI of lower than 100 lx (89 lx in the morning, 92 lx at noon, and 81 lx in the afternoon). On 21 March, LB_{3-4} are the only configurations with acceptable illuminance levels in zone C; however, they fail to reach the lower threshold of illuminance in zone A. On 22 June, although LB_{1-4} are the only layouts with acceptable illuminance value in zone C, they record eWPI of lower than 100 lx in zone A. In general, for south orientation, C_1, L_{1-2}, and B_{1-2} have acceptable illuminance levels in the farthest zone from the window. At the same time, L_{3-4}, B_{3-4}, and LB_{1-3} show allowable results in the middle zone, while LB_{3-4} are the best layouts with acceptable daylight level in the most critical part of the room in terms of sunlight quantity (zone C).

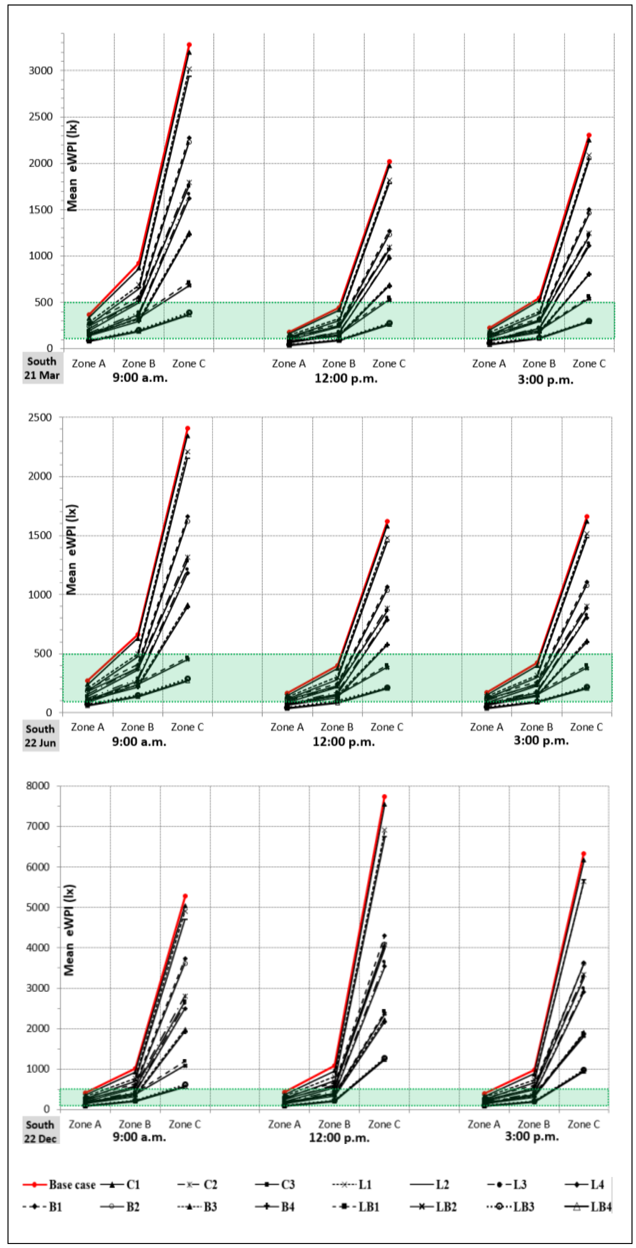


Figure 7 Mean eWPI recorded by 16 configurations in the south-facing room

The largest differences of daylight level in the modelled room are recorded for east orientation, as shown in Figure 8. It is evident that the east-facing room receives the highest eWPI in zone C in the morning with 17,697 lx (21 March), 15,969 lx (22June), and 11,651 lx (22 December).

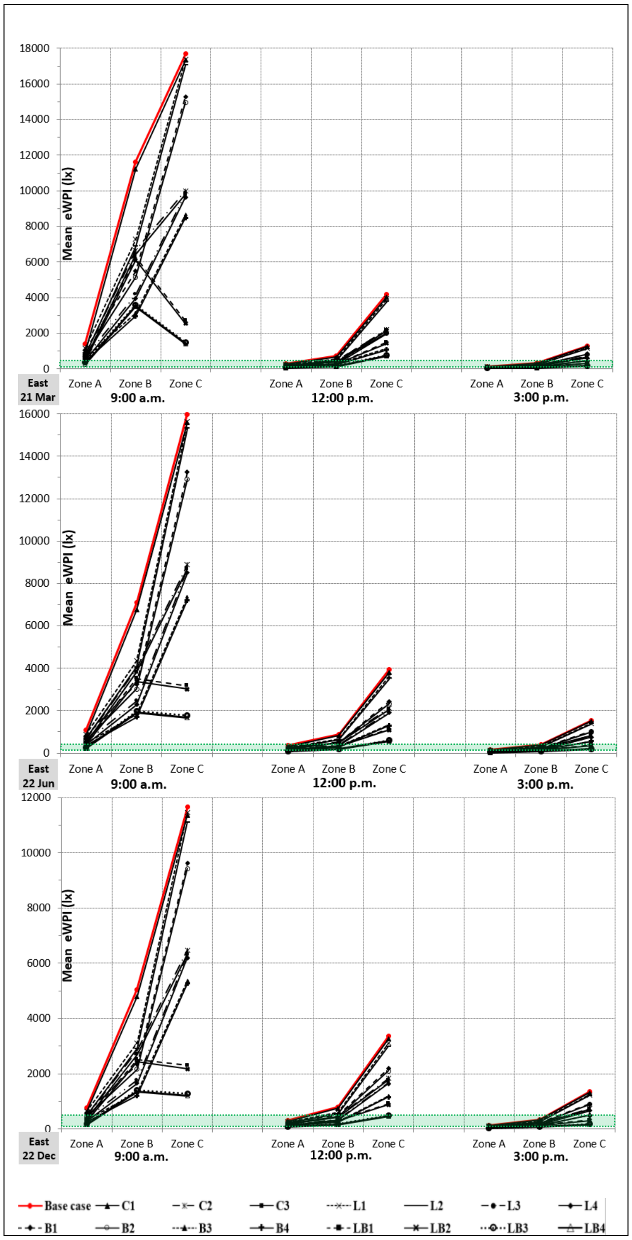


Figure 8 Mean eWPI recorded by 16 configurations in the east-facing room

Simultaneously, none of the layouts represent allowable illuminance in zones C and B, whereas $L_{3\text{-}4}$, $B_{3\text{-}4}$, and $LB_{1\text{-}4}$ record acceptable results in zone A. The general principle is that by increasing distance from the room's window, eWPI values are decreased from zone C to zone A. However, this general pattern is not followed by $LB_{1\text{-}4}$ in the mornings since the eWPI values are peaked in the middle part of the room. This is because at 9:00 a.m., the sun is located lower in the sky with an altitude of 26°, hence the east-facing room with a partial blind at the lower part of the window ($LB_{1\text{-}4}$) directly obstructs sunlight penetration in zone C. However, sunlight streamed without any obstruction through the window in zone B causing a higher daylight level than zone C. On the whole for east orientation, L_4, B_1, B_4, and LB_2 have allowable eWPI in the farthest zone from the window for all tests, while $C_{2\text{-}3}$, $L_{3\text{-}4}$, $B_{1\text{-}4}$, and $LB_{1\text{-}2}$ show acceptable daylight level in zone B for the studied times excluding the mornings when the room receives intense sunlight. Moreover, $LB_{3\text{-}4}$ represent admissible eWPI in the nearest zone to the window except for the morning times.

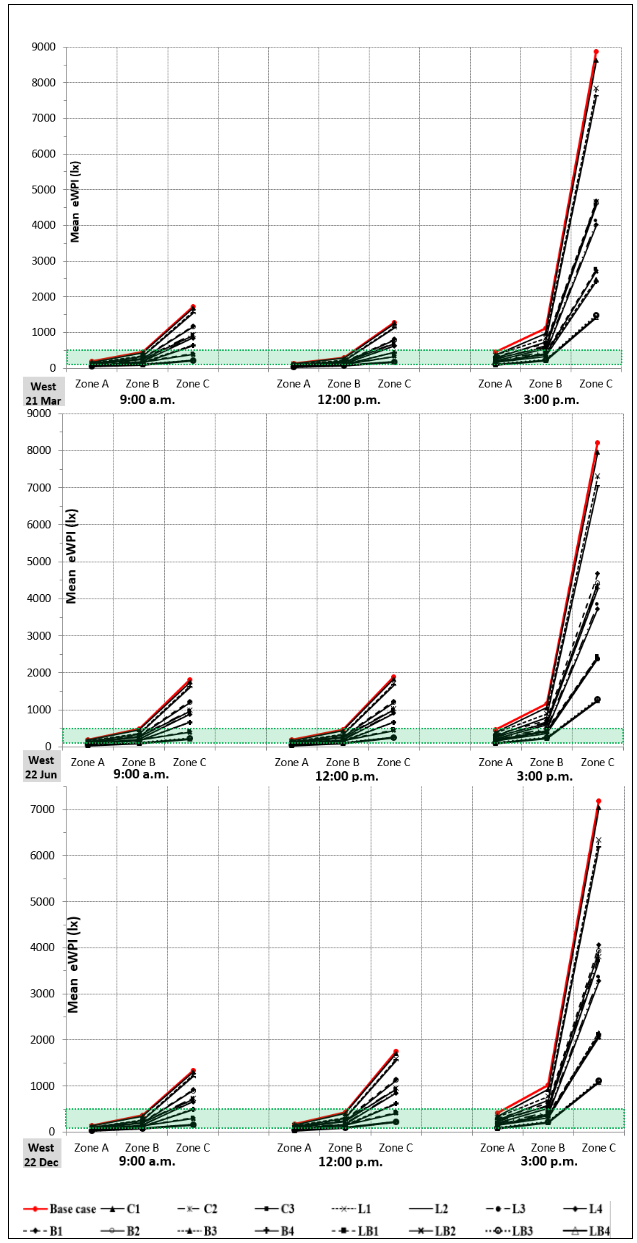


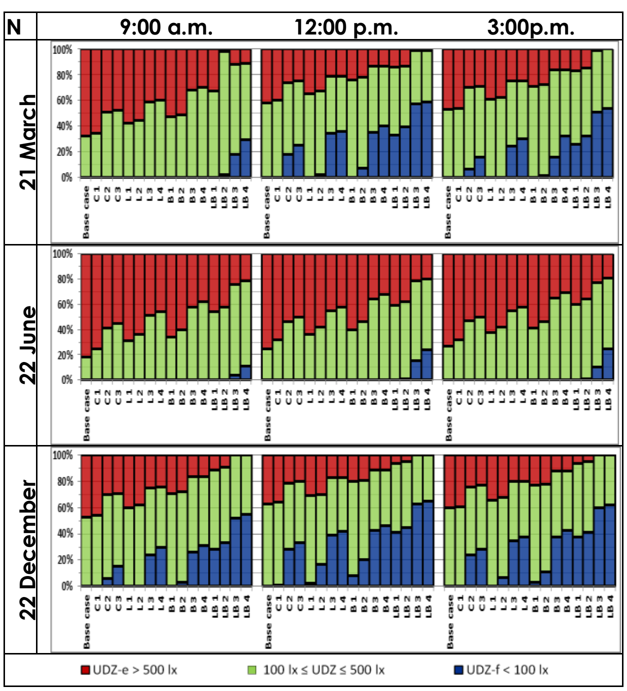
Figure 9 Mean eWPI recorded by 16 configurations in the west-facing room

As shown in Figure 9, the most critical time of daylight availability in the west-facing room is afternoons when the base case yields eWPI of 8,878 lx (on 21 March), 8,212 lx (on 22 June), and 7,184 lx (on 22 December) in zone C. At the same time, none of the configurations record allowable illuminance in this zone during the afternoon. In general, C_1, L_1, and B_1 have allowable eWPI in the farthest zone from the window while L_3, L_4, $B_{3\text{-}4}$, and $LB_{1\text{-}2}$ record acceptable eWPI in the middle zone for west orientation. Moreover, $LB_{1\text{-}4}$ are the only layouts with acceptable eWPI in zone C till midday, whereas in the afternoon, $LB_{3\text{-}4}$ have the highest impacts among all configurations on the reduction of the intense daylight level (around 84%) in the nearest zone to the window.

3.2 UDZ Analysis

Table 6 illustrates the percentage of the room with UDZ-f, UDZ, and UDZ-e recorded by all sixteen interior configurations for north orientation. In general, the base case has the highest UDZ-e (almost 82%) compared with the other layouts. On 21 March, LB_2 has the best UDZ performance (96% in the morning) while $B_{1\text{-}2}$ are the best layouts from midday onwards with UDZ of more than 70%. Moreover, LB_4 makes the biggest zone with an illuminance of lower than 100 lx in the room during the whole day (almost 59% recorded for UDZ-f). On 22 June, the base case yields the minimum UDZ of around 20% and the maximum UDZ-e of around 80% in the room. Furthermore, those configurations, including the tinted window film, show much higher UDZ than those with the clear one. LB_3, with a notable 300% increase of UDZ compared to the base case, is the best configuration among all in the morning, while B_4 shows the highest UDZ with 172% and 156% increase compared to the base case at midday and in the afternoon, respectively. LB_4 is the worst layout in terms of UDZ-f performance during the whole day. On 22 December, although $LB_{3\text{-}4}$ show no percentage of UDZ-e in the room, they record the highest UDZ-f with averagely 53% at 9 a.m., 64% at 12 p.m., and 61% at 3 p.m. Besides, B_1 makes the best UDZ with an average of 72% during the whole day.

Table 6 Percentage of UDZ-f, UDZ, and UDZ-e recorded by the sixteen configurations in the north-facing room



For south orientation on 21 March (Table 7), $LB_{3\text{-}4}$ record the highest UDZ (71%) among other layouts in the morning, whereas B_1 and B_2 show the best UDZ performance with an average of about 70% from midday onwards. Although LB_4 causes no percentage of UDZ-e in the room, it records the highest UDZ-f among all, with 29% in the morning, 59% at noon, and 54% in the afternoon. On 22 June, while there is no UDZ-e percentage by $LB_{3\text{-}4}$, they make the worst scenario in terms of UDZ and UDZ-f performance during the whole day, especially at midday. Furthermore, LB_1 yields the best UDZ performance with 70% in the morning, whereas B_1 is the best configuration with the UDZ of 77% at noon and 73% in the afternoon. On 22 December, the base case records the minimum UDZ (lower than 30%) and the maximum UDZ-e (higher than 70%) during the whole day. The direct incidence of sunbeams in the south-facing room on 22 December, when the sun has the lowest altitude in the sky, made those layouts with the tinted window film represent much better UDZ performance than the layouts with the clear window film. At the same time, $B_{3\text{-}4}$ have the highest UDZ among all, with an average of 67% during the whole day. Although LB_4 could significantly reduce the UDZ-e percentage in the room, it makes a quarter of the room to be covered with UDZ-f.

For east orientation, as shown in Table 8, the base case yields daylight levels of higher than 500 lx in the whole room during the mornings. In addition to the base case, $C_{1\text{-}2}$, $L_{1\text{-}3}$, $B_{1\text{-}3}$, and LB_1 on 21 March; C_1, L_1, and B_1 on 22 June; L_1 and B_1 on 22 December record UDZ-e of 100% in the morning.

Table 7 Percentage of UDZ-f, UDZ, and UDZ-e recorded by the sixteen configurations in the south-facing room

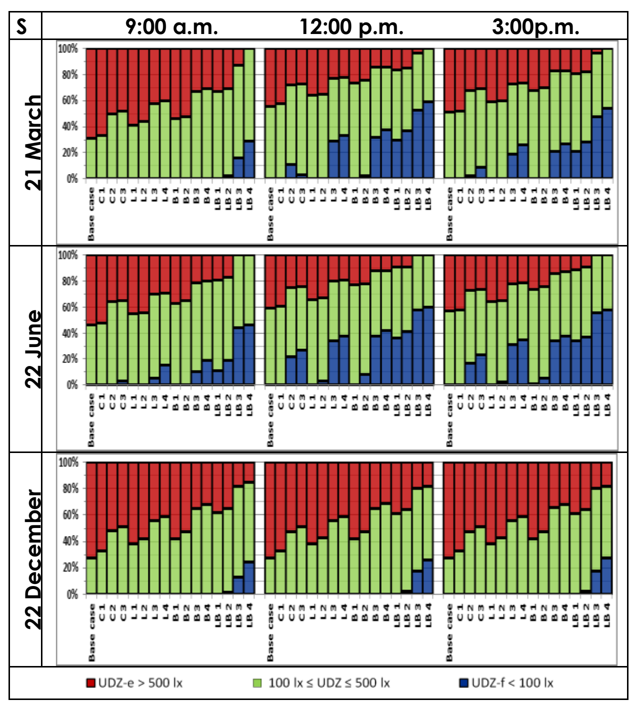


Table 8 Percentage of UDZ-f, UDZ, and UDZ-e recorded by the sixteen configurations in the east-facing room

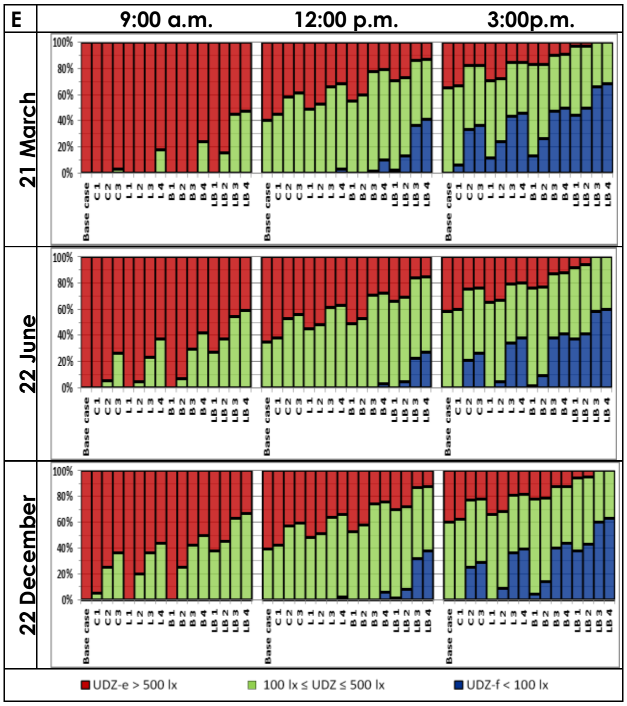
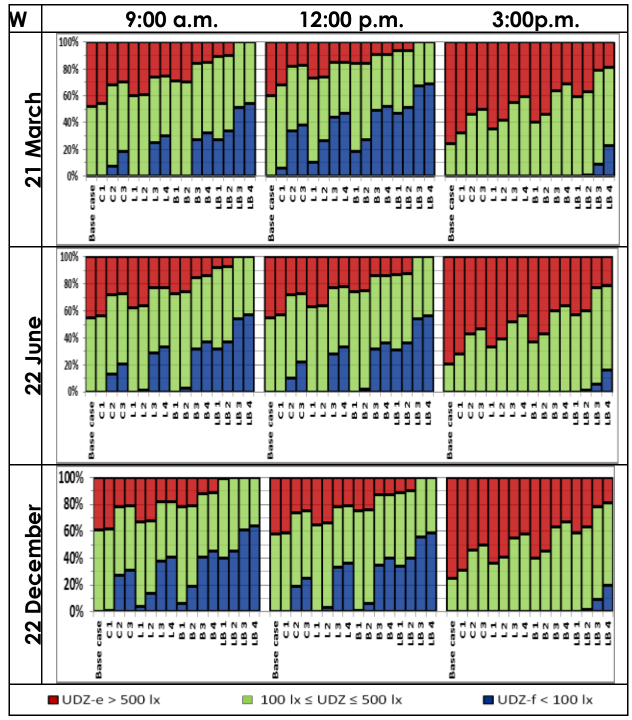


Table 9 Percentage of UDZ-f, UDZ, and UDZ-e recorded by the sixteen configurations in the west-facing room



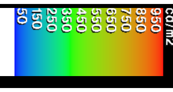
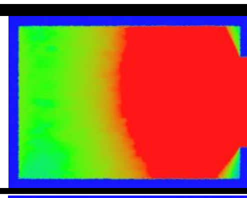
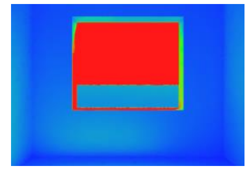
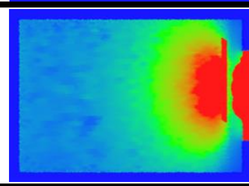
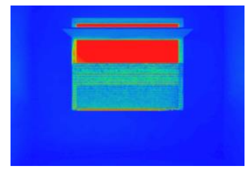
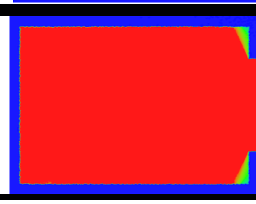
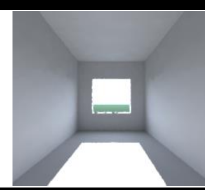
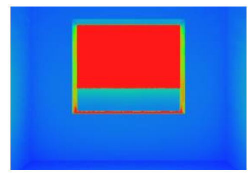
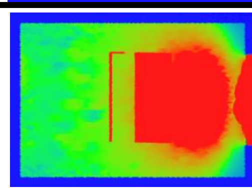
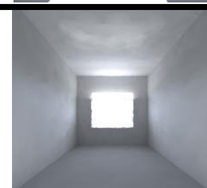
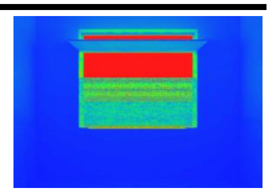
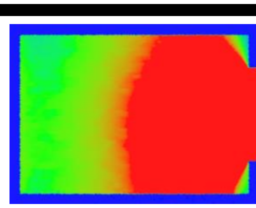
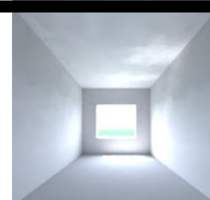
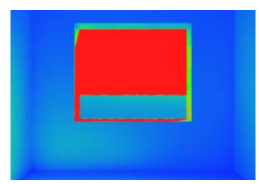
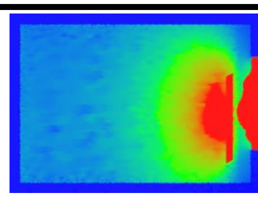
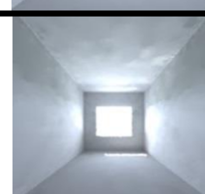
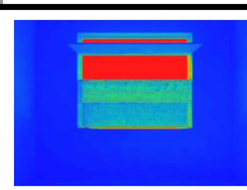
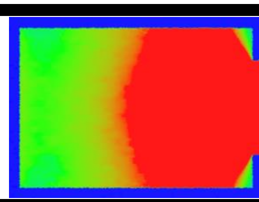
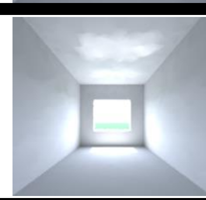
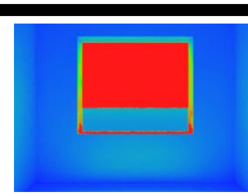
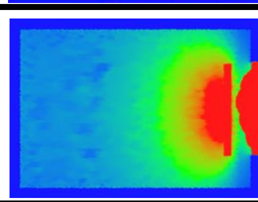
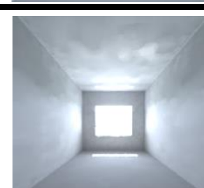
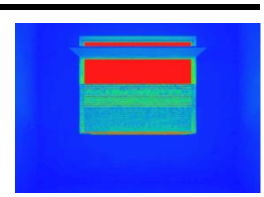
Among all, LB_{3-4} have the highest impacts on the increase of UDZ from zero to about 46%, 58%, and 65% in March, June, and December, respectively. At midday, B_3 shows the highest UDZ with 77% (21 March), 71% (22 June), and 74% (22 December), and LB_4 is the worst layout in terms of UDZ-f performance with about 41%. In the afternoons, all layouts record UDZ-f in the room except C_1 and L_1 in June and December; Furthermore, B_1 records the highest UDZ with about 70%. Although LB_{3-4} could completely remove UDZ-e in the room, they record the worst UDZ-f performance among all with an average of 67% (21 March), 59% (22 June), and 61% (22 December) in the afternoon.

For west orientation, as illustrated in Table 9, although LB_{3-4} could significantly remove UDZ-e in the room compared with the base case from morning till noon, they increase UDZ-f to an average of around 60%. Moreover, B_1 shows the best daylighting performance among all layouts, with an average of 72% UDZ. In the afternoons, the base case causes around 75% of the room to have an illuminance of higher than 500 lx. At the same time, LB_3 shows the best performance compared with the other layouts with about 70% UDZ and less than 10% UDZ-f, while LB_4 has the highest UDZ-f among all with an average of 20%.

3.3 Glare Analysis

To analyze glare in the room, the most critical times were considered for each orientation under the intermediate sky as the predominant sky condition in tropical regions. Based on the illuminance findings, north, and south-facing rooms have recorded the worst daylighting performance at midday (i.e., maximum eWPI and minimum UDZ) on 22 June and 22 December, respectively. Besides, east and west-facing rooms have recorded the worst scenarios of daylighting on 21 March in the morning and afternoon times, respectively. As shown in Table 10, LB_3 is the best among all configurations with the lowest eWPI value and the highest UDZ percentage compared with the base case. The mean DGP for the base case in the north-facing room is 0.42 representing a disturbing glare condition in which LB_3 could successfully decrease DGP to 0.31, showing an imperceptible condition. In the south-facing room, DGP is decreased from 0.44 to 0.33 by the optimum configuration. In the east-facing room, the base case records a DGP of 0.53, which shows the intolerable condition of glare in the modelled room. LB_3 could significantly decrease the DGP value to 0.37 in the east-facing room, showing a perceptible condition. For west orientation, the DGP value is considerably reduced by LB_3 from 0.47, as the intolerable glare condition, to 0.36 as the perceptible condition of glare in the modelled room.

Table 10 Comparison of the base and optimum configurations for the worst-case scenario of each orientation

Condition		Daylight Metric (mean)	Illuminance 	Luminance	
North (22 Jun, 12 p.m.)	Base case	eWPI = 2,961 lx UDZ = 25% DGP = 0.42			
	LB_3	eWPI = 513 lx UDZ = 64% DGP = 0.31			
East (21Mar, 9 a.m.)	Base case	eWPI =10,228 lx UDZ = 0% DGP = 0.53			
	LB_3	eWPI = 1,735 lx UDZ = 45% DGP = 0.37			
South (22 Dec, 12 p.m.)	Base case	eWPI = 3,081 lx UDZ = 27% DGP = 0.44			
	LB_3	eWPI = 526 lx UDZ = 63% DGP = 0.33			
West (21 Mar, 3 p.m.)	Base case	eWPI = 3,473 lx UDZ = 24% DGP = 0.47			
	LB_3	eWPI = 608 lx UDZ = 67% DGP =0.36			

Based on the daylight simulation findings of this paper under a tropical intermediate sky, daylight levels are extremely high in an existing home-office room, including a bare window without shading controls. In this regard, the average illuminance level on the working surface in the east-facing room is as high as 10,228 lx in the morning on 21 March, far beyond the permissible range. Simultaneously, the whole space of the room is brightened by direct sunlight with an intensity of much higher than 500 lx. Excessive indoor daylight quantity causes intolerable glare conditions in the room where DGP is as high as 0.53. Thus, it is necessary to reduce the abundance of indoor daylight to improve visual comfort in existing home office buildings in tropical regions.

3.4 Optimum Design Configurations for Tropical Daylighting

The eWPI analyses reveal that B_1, with the specifications of a partial blind at the upper part of the window, a clear window film, and the upper-threshold reflectance of the room's surfaces, is the only configuration with allowable daylight level in the farthest area from the window; while those layouts including the partial blind with tinted film ($B_{3\text{-}4}$) and those of the integrated shading system with the clear film ($LB_{1\text{-}2}$) show admissible daylighting performance within the middle space of the home office room for various locations of the sun in the tropical sky. For the most critical part of the home office room regarding direct sunlight incidence, those configurations, including the integrated shading system with the tinted window film ($LB_{3\text{-}4}$), record acceptable daylight levels for diverse times and orientations. Although $LB_{3\text{-}4}$ yield the mean eWPI value of 1,735 lx during the presence of the most severe glare in the home office room (i.e., east orientation in the morning on 21 March), they could significantly 83% soften the intensity of indoor daylight level for such a critical time.

The results of UDZ clarified that the integrated shading system provides much better indoor daylighting performance than a single light shelf or a partial Venetian blind on a window receiving direct sunlight. It stems from the fact that the integrated shading system has a high potential to transmit incident sunlight towards the room’s ceiling and to reduce immediate glare from the window. Consequently, $LB_{3\text{-}4}$ have the best indoor daylighting performance among all in the whole room when directing sunlight penetration. However, $LB_{3\text{-}4}$ are not efficient for daylighting in the room with the presence of diffused or reflected sunlight in which they increase the lower-limit illuminance zone (eWPI < 100 lx), particularly in the rear part of the room. In this case, $B_{1\text{-}2}$ represent the best daylighting performance among all in the room with diffused or reflected daylight.

Table 11 shows the optimum configurations with the best daylighting performance for each orientation and time in the existing home office buildings. The optimized layout has been set to maximize UDZ, minimize UDZ-f and UDZ-e, and have a mean eWPI of 100-500 lx. Accordingly, B_1, B_3, and LB_3 are the optimum layouts for various times and orientations. The common component of these optimum layouts is the partial venation blind. Hence a partial Venetian blind can be a significant parameter to retrofit interior spaces in existing home office rooms with the typical size as it has high potentials to provide comfortable visual environments in tropical climates. Several research in tropical contexts indicates that daylighting performance could be improved by using an internal light shelf in buildings with an open-plan design [50,60,72,73]. As the depth of room in those buildings exceeds the maximum depth for the daylit space from a side-lit window, internal light shelves could reflect daylight for deeper penetration and create admissible illuminance levels for spaces far from the window. However, the findings of this paper show that those layouts with a single light shelf ($L_{1\text{-}4}$) could not provide efficient tropical daylighting in existing home office buildings in which the whole room can be completely brightened by direct sunlight. Accordingly, using a partial horizontal blind is more practical than a single light shelf to control sunlight penetration in such buildings. It can be deduced that the depth of a side-lit room is a significant criterion to use an appropriate type of internal shading device to enhance indoor daylighting in home office buildings. Table 11 also shows that all the optimum layouts have the upper reflectance thresholds for the room's surfaces. This is following a study by Nasrollahi and Shokry [54] that proved the reflectivity coefficients of 0.6 (walls) and 0.4 (floor) are highly effective for daylighting of desk-related workspaces.

3.5 Impact of Interior Design Parameters on Tropical Daylighting

By classification of all the 16 design configurations into two groups (i.e., the lowest and the highest thresholds for reflectance values of the room's surfaces), the mean relative difference of eWPI between these two groups is on average 4% in zone C, 9% in zone B and 17% in zone A. Accordingly, as the distance from the side-lit window in a typical home office room gets longer, the influence of the room's surfaces on the reduction of indoor daylight quantity seems more obvious. In general, using the lowest thresholds of reflectance (ceiling/walls/floor = 60/35/15) for interior surfaces instead of the highest values (ceiling/walls/floor = 90/60/35) could only 5% reduce daylight intensity in the home office room. Thus, reflectivity values of interior surfaces could not significantly soften the abundance of indoor daylight in existing home office buildings in tropical climates. However, higher reflectance values and light-colored surfaces could distribute daylight more uniformly in a building and provide lower contrast for spaces far from the window.

When the design configurations are set in two groups, those with the clear window film and those with the tinted one, the mean relative difference of eWPI between the clear and tinted layouts is 47% for each space of the home office room. Hence, indoor daylight intensity could approximately be halved in buildings through installation of a tinted film *(vt* = 50%) on the window glazing in a typical home office room. Thus, when a side-lit window is faced with directing sunlight penetration, a tinted film can be more efficient than a clear one for tropical daylighting since tinted window films could reflect much more direct sunlight to the outside compared with the clear ones. However, with diffused or reflected sunlight in home office workspaces, those layouts with clear window films could be more effective than the tinted ones for tropical daylighting and view appreciation in buildings.

The mean relative difference of eWPI between the layouts with a light shelf (L_{1-4}) and those without it (base case and C_{1-3}) is on average 8% in zone C, 30% in zone B, and 19% in zone A. Thus, a single internal light shelf has the lowest influence on reducing tropical daylight intensity in the nearest zone to the window. By installing an internal light shelf on a bare window, the mean daylight level could average, 15%, be reduced in a home office room. Previous studies in tropical climates prove that an internal light shelf is a significant daylighting approach in deep office rooms [50], [74]. However, the findings of this paper reveal that a single internal light shelf could not soften the intense daylight level in home office rooms with a typical depth of 4.5 meters. Thus, it is not a profitable strategy for tropical daylighting in existing home office workspaces.

The mean relative difference of eWPI between the layouts including a partial Venetian blind (B_{1-4}) and those without it (base case and C_{1-3}) is on average 31% in zone C, 42% in zone B, and 25% in zone A; thus, using a partial blind at the upper part of the window has showed the lowest impact on reducing intense tropical daylight in the farthest zone to the window.

Table11 Optimum configurations for efficient tropical daylighting in existing home office buildings in tropical climates

	21 March			22 June			22 December		
	9:00	**12:00**	**15:00**	**9:00**	**12:00**	**15:00**	**9:00**	**12:00**	**15:00**
South	LB_3	B_1	B_3	B_3	B_1	B_1	LB_3	LB_3	LB_3
West	B_1	B_1	LB_3	B_1	B_1	LB_3	B_1	B_1	LB_3
North	LB_3	B_1	B_3	LB_3	LB_3	LB_3	B_1	B_1	B_1
East	LB_3	B_3	B_1	LB_3	LB_3	B_1	LB_3	B_3	B_1

B_1 : Surface reflectance: (ceiling/walls/ floor) ~ (90/60/35) - Clear window film (*vt* = 80%) - Partial blind at the upper part of the window
B_3 : Surface reflectance: (ceiling/walls/ floor) ~ (90/60/35) - Tinted window film (*vt* = 50%) - Partial blind at the upper part of the window
LB_3 : Surface reflectance: (ceiling/walls/ floor) ~ (90/60/35) - Tinted window film (*vt* = 50%) - light shelf with Partial blind at the lower part of the window

Installation of a partial blind at the upper part of a window could, on average, 35% reduce the mean daylight availability in the home office room. While a light shelf has more potential to distribute daylight deeper in a home office room, a partial blind operates much better in controlling sunlight penetration in the closer spaces to a window. Hence the effect of a partial blind on the reduction of indoor daylight quantity is much more sensible than a single internal light shelf in a home office room with a typical depth of 4.5 meters. Findings of this paper have showed that during the presence of indirect sunlight (diffused or reflected) in the home office room, those layouts with a single partial blind (B_{1-4}) have better daylighting performance than those with the integrated shading system (LB_{1-4}) since the latter makes much more spaces in the room with an illuminance of lower than 100 lx.

The mean relative difference of eWPI between the configurations with the integrated light shelf-partial blind (LB_{1-4}) and those without this system (base case and C_{1-3}) is on average 76% in zone C, 58% in zone B, and 55% in zone A. Thus, as the distance gets closer to the side-lit window in a typical home office room, the influence of this integrated shading system on the reduction of indoor daylight availability is more perceptible. Whenever a single light shelf is integrated with a partial blind (at the lower part of a window), this system could significantly 70% soften the intensity of tropical daylight in a typical home office room.

Based on the results of a survey in several home office buildings under the tropical sky, conducted by the authors [7], users apply curtains and blinds to inhibit the intense solar light and glare inside their existing home office rooms. However, these conventional shading models, which can be fully pulled down, may completely block the penetration of natural lighting. Hence, home office workers use electric lighting instead for doing their desk-related tasks during the daytime. This study suggests an interior shading design that can be used instead of the conventional shading models through controlling the incident of excessive sunlight in home office workspaces. This interior shading strategy consists of an integrated system of a light shelf with a partial Venetian blind that can be a significant solution to obstruct the immediate penetration of direct sunlight in existing home office buildings in tropical contexts.

4.0 CONCLUSION

This paper is focused on different internal design parameters to retrofit existing home office workspaces for efficient tropical daylighting. Intense external luminance and severe solar radiation in tropical climates cause visual discomfort in many existing buildings, particularly home office workspaces that are mostly designed with no external shading controls. Hence, it is essential to soften indoor daylight availability in existing home office buildings, with their typical room's depth of about 4.5 m, to provide efficient daylighting for home office users. As the intermediate sky is the most predominant and problematic sky type in the tropical climate of Malaysia, this sky type was applied for the simulation tests. The simulated results, taken from Radiance-IES, were compared with the measured results, taken from the field measurement, to validate the accuracy of software under the tropical skies.

Among different interior design parameters, the reflectance of surfaces has a minor impact of around 5% on reducing intense tropical daylight in the home office room. A partial blind with a 35% decrease of indoor daylight level is more beneficial for improving tropical daylighting performance than an internal light shelf with a 15% reduction of daylight quantity in the typical home office room. Moreover, the impact of a tinted window film on the reduction of indoor daylight availability is more perceptible than a single internal light shelf or a partial blind. Among all the studied design parameters in this research, the integrated internal light shelf with a partial blind (at the lower part of the window) has the highest impact of around 70% on reducing intense tropical daylight level in existing home office buildings. When this integrated shading system is installed on a tinted window, i.e., LB_3, the whole system could efficiently around 85% soften the excessive tropical daylight quantity in existing home office buildings.

Overall, this research proved that various configurations can be introduced as the optimum form for efficient tropical daylighting in the home office room with different conditions of daylight availability. Thus, a fixed interior design model cannot be efficient for tropical daylighting in home office buildings during different times and even for various orientations. It can be concluded that a dynamic model of internal shadings might be a solution for tropical daylighting in existing home office buildings. The configuration of this dynamic shading system and how it operates for different conditions of tropical skies needs further research. Future studies can also be focused on the impact of other interior shading controls such as screens, smart glazing, etc., on daylighting performance in typical home office workspaces in existing buildings.

Acknowledgement

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