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Daylighting Performance of Integrated Venetian Blinds with Horizontal Light Pipe System for Deep Plan High-Rise Office in Tropical Climate

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ABSTRACT

A substantial amount of daylight is received by tropical countries like Malaysia. There are advantages and disadvantages to using this renewable resource in a high-rise office building. Such buildings' deep plan spaces make it difficult to create a uniform daylight distribution across the space. A solution for this issue is the usage of an integrated Venetian blind (VB) with a horizontal light pipe (LP). Using an overcast and intermediate sky in South orientation, seven (7) distinct types of VB angle configurations were simulated using the Integrated Environment Solution Virtual Environment (IESVE) to evaluate how well they performed in daylight with an integrated LP. The findings demonstrated that the daylight uniformity throughout the room was improved by the integration of the VB and LP systems. When compared to a room with only a LP installed, VB with 0° and -15° angles had the best performance. The combination of LP and VB allowed for the shading of the front portion of the space and at the same time, illuminating the rear portion of the space. The results of this study encourage building designers to utilise the integrated VB and LP in the deep open-plan high-rise office building and reduce the use of non-renewable energy resources.

1. Introduction

Malaysia, which experiences tropical climate, receives high amounts of daylight consistently throughout the year. The high occurrence of intermediate sky adds to the availability of daylight (more than 20, 000 lx), especially between 09:00 and 17:00 hrs [1]. This creates an opportunity for offices in Malaysia to utilise this renewable energy resource where only a small fraction of illumination (300-400 lx) is required to meet the lighting standard through the means of building envelope [2-7]. Offices which allow daylight penetration offers great benefits to the occupants in terms of physiological and psychological. This, in turn, decreases absentees and increases the productivity of the office workers. The use of daylight also offers reductions in cooling loads because daylight generates less heat than electrical illumination with equivalent light levels and thus, reduce the carbon emission [8-13].

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With the increase of high-rise offices that adopt deep, open plan due to maximising profit from the marketable floor area, providing natural illumination in such buildings offer a challenge. The contrasting level of light across such rooms, usually more than 10m in depth, is caused by a high illumination in the area near the window opening and low to none at the other end of the space [14]. Hence, proper intervention such as light distribution system is required to solve the problem.

Studies have shown that horizontal light pipe (LP) has the potential to transport daylight and illuminate the deep interior of such rooms [15-18]. Although vertical LP provides an alternative to distribute the daylight, it is not feasible to be applied in a high-rise building as it sacrifices valuable space for daylight transport from the rooftop to the floors below compared to horizontal LP which can be retrofitted at plenum spaces [14,19,20,21]. However, although the deep interior can be illuminated up to 100-300 lx, there is still a high daylight penetration at the front portion of the room that receives more than 500 lx, and this causes visual discomfort [1]. According to the author's preliminary research, integrating shading devices with LP has the potential to attain a more uniform daylight distribution [15].

This study seeks to explore the integration of Venetian blinds (VB) with horizontal LP to achieve optimum utilisation of daylight in a deep open-plan high-rise office building in a tropical climate through the simulation tool, Integrated Environment Solution Virtual Environment (IESVE). Although there are previous studies on VB that shows its potential to illuminate and shade a space, they are only limited to shorter-span spaces [22-24]. This study also employs Daylight Factor (DF), daylight ratio with estimated indoor illuminance (EII), and work plane illuminance ratio to assess daylight performance. The average estimated exterior global illuminance values from the tropical climate which were 27,104 lx, 84,613 lx, and 74,991 lx for 09:00 hrs, 12:00 hrs, and 15:00 hrs were used for the purpose of this study [14].

2. Methodology

This study used IESVE as a simulation tool to evaluate daylight performance on the integration of LP and VB. The required geometrical models, such as the room, LP, and shading device, can be built by the software. Additionally, the ray-tracing approach is used for calculation in the software's Radiance simulation engine where the calculation method takes into account the surface's values for reflection, transmission, and refraction. Previous studies have validated the software [12,14,25,26].

IESVE has a variety of sky components for simulation, including uniform cloudy, 10k lx standard International Commission on Illumination (CIE) overcast, intermediate sky with sun, intermediate sky without sun, standard clear, sunny, and CIE overcast. The absolute illuminance values from the work plane illuminance can be converted into relative ratios between the indoor and outdoor illuminance values, such as the daylight ratio, in order to lessen the differences between these sky models and tropical sky conditions, where the latter tend to have lower values. This has been shown in previous studies [9,14]. Equation (1) is used to calculate the values of the daylight ratio.

$$DR = \frac{WPI}{Exterior\ Global\ Horizontal\ Illuminance} \tag{1}$$

where DR is the daylight ratio, and WPI is the work plane illuminance value.

2.1 Daylighting Simulation

Seven configurations of VB and a base case were used for simulation as shown in Table 1. The VB configurations differ in terms of the angles, i.e., +45˚, +30˚, +15˚, 0˚, -15˚, -30˚, and -45˚ (Figure 1), which affect the reflection of light and shading based on the sun's altitude. South orientation was chosen due to the site's geographical position which is north of the Equator [14]. This enables the room to receive daylight throughout the day.

As illustrated in Figure 2, a deep plan office space with a semi-circle LP that served as a base case was modelled in IESVE. It measured 6.0m x 12.0m x 2.7m with a 0.55 window-to-wall ratio (5.6m x 1.6m), which is based on a typical high-rise office facade. With two openings for interior lighting distribution and room depth, the semi-circle LP has a 2.0m diameter. Each opening measures 2.0m by 2.0m. Table 2 shows the surface properties of the model, including specularity, reflectance, roughness, type, and visible transmittance.

Table 1
Configuration of variables, orientations, time, and design days

Name	VB Angle (°)	Orientation	Time and Design Days
Base Case	NA	South	09:00, 12:00, and 15:00 21st March, 22nd June, and 22nd December
VB1	+45°		
VB2	+30°		
VB3	+15°		
VB4	0°		
VB5	-15°		
VB6	-30°		
VB7	-45°		

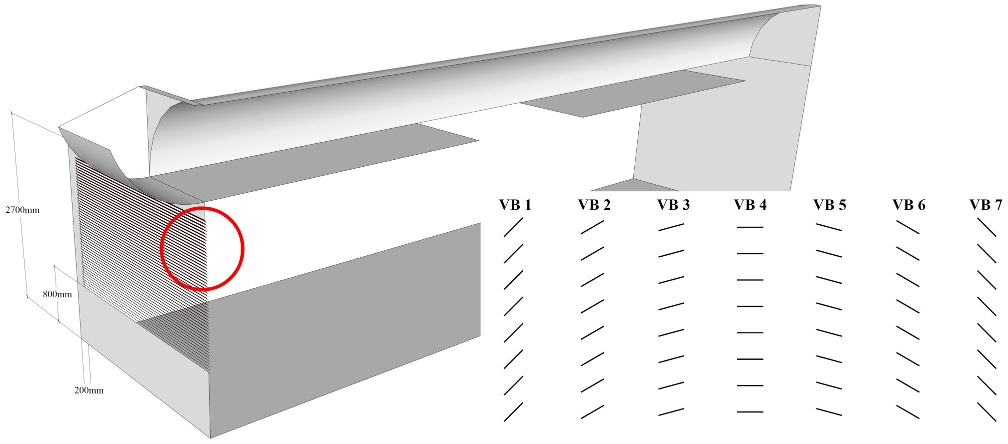


Fig. 1. Configuration of VB with various angles

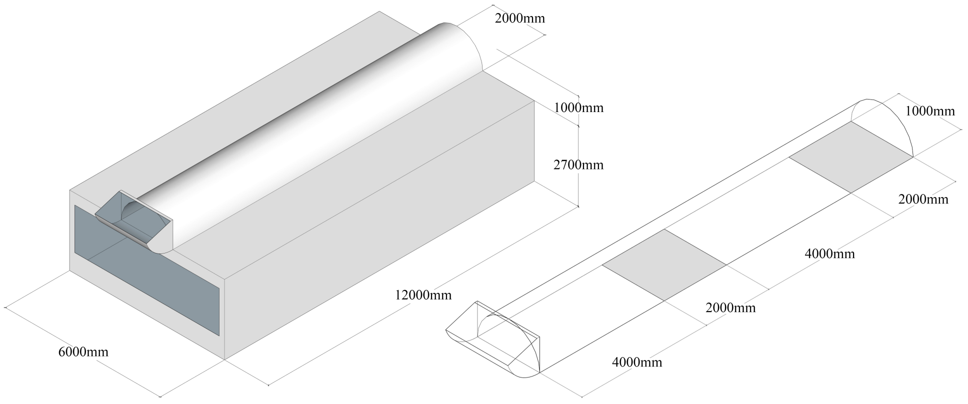


Fig. 2. Model of simulation room with semi-circle LP with two openings as base case configuration

Table 2
surface properties of the model

Surface	Reflectance (%)	Specularity (%)	Roughness Value	Type	Visible Transmittance (%)
Wall	70	0.03	0.03	Plastic	N/A
Floor	20	0.03	0.20	Plastic	N/A
Ceiling	80	0.03	0.03	Plastic	N/A
LP	99	0.05	0.03	Metal	N/A
VB	99	0.05	0.03	Metal	N/A
Glazing	N/A	N/A	N/A	N/A	0.75

The simulation procedure used 10k lux cloudy sky and CIE intermediate sky with the sun with three timings (09:00 hrs, 12:00 hrs, and 15:00 hrs) and three design days (21st March, 22nd June, and 22nd December). For analysis, the work plane illuminance values for these simulations were gathered.

2.2 Criteria of Analysis

Equation (2) shows the calculation for DF, where the performance of each case in a worst-case scenario using overcast sky was evaluated. Figure 3 shows the three divisions of the room to assess daylight performance.

$$DF = \frac{Indoor\ Work\ Plane\ Illuminance}{Exterior\ Global\ Horizontal\ Illuminance}\ x\ 100\% \tag{2}$$

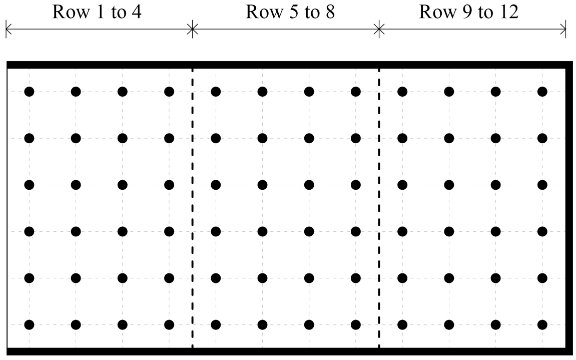


Fig. 3. Division of room into three areas based on distance from the room opening: Row 1 to 4, Row 5 to 8, and Row 9 to 12

In this study, the performance of daylight was evaluated using estimated interior illuminance. The EII was calculated using Equation (3), by utilising the daylight ratio to represent the indoor daylight level under a tropical sky. An average estimated exterior global illuminance values for 09:00 hrs, 12:00 hrs, and 15:00 hrs were utilised [14]. They were 27,104 lx, 84,613 lx, and 74,991 lx. Equation (4) was then used to calculate the work plane illuminance ratio to assess the uniformity of the work plane illumination.

$$Estimated\ indoor\ illuminance = \frac{Daylight\ Ratio}{100}\ x\ Estimated\ exterior\ global\ horizontal\ illuminance\ x\ 100\% \tag{3}$$

$$Work\ Plane\ Illuminance\ Ratio = \frac{Emin}{Eavg} \tag{4}$$

where E_{min} is the minimum illuminance, and E_{avg} is the average illuminance measured at the work plane level.

3. Results and Discussion

Figure 4 shows the DF performance for VB cases when compared to the base case. For rows 1-4, all the VB cases reduced the base case's DF of 8.88% to the range of 0.70-6.01%. This translated to a reduction of 32.38-92.11%. VB2 and VB3 showed the best performance among the VB cases in rows 1-4 with DF 1.54% and 2.55%, respectively, where the two figures fall in between the recommended range of DF 1.0-3.5%. VB4 has a DF of 3.53% which is just slightly above the recommended range. All the VB cases also managed to reduce the maximum DF of the base case by as much as 20.52-69.65% where VB1 showed the best performance.

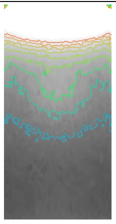
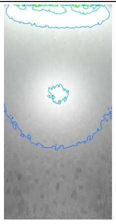
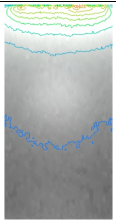
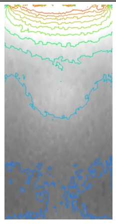
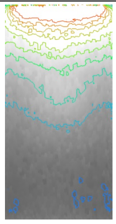
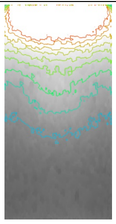
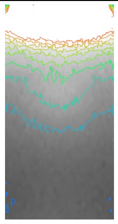
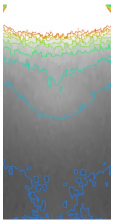
Results		Cases (South)							
		BC	VB1	VB2	VB3	VB4	VB5	VB6	VB7
Simulated Indoor Illuminance	LUX 475 425 375 325 275 225 175 125 75 25								
Daylight Factor (%)	Minimum	0.28	0.08	0.11	0.16	0.21	0.27	0.23	0.17
	Maximum	25.73	7.81	8.63	18.34	10.10	12.42	16.54	20.45
	Row 1-4	8.88	0.70	1.54	2.55	3.53	4.88	6.01	5.81
	Row 5-8	1.13	0.42	0.41	0.69	0.92	1.15	1.01	0.74
	Average	2.95	0.40	0.62	1.04	1.43	1.94	2.17	1.98
% of changes in DF	Minimum		-71.43	-60.71	-42.86	-25.00	-3.57	-17.86	-39.29
	Maximum		-69.65	-66.46	-28.72	-60.75	-51.73	-35.72	-20.52
	Row 1-4		-92.11	-82.63	-71.30	-60.26	-45.06	-32.38	-34.55
	Row 5-8		-63.06	-63.94	-39.63	-18.80	1.43	-11.31	-34.48
	Average		-86.44	-78.98	-64.75	-51.53	-34.24	-26.44	-32.88

Fig. 4. DF performance of base case and VB cases

The EII results for the base case and VB cases are shown in Figures 5-7. Throughout the whole nine (9) results, the base case's EII at rows 1-4 were reduced significantly. Generally, VB1 and VB2 showed the most significant reduction in rows 1 and 2. In March, the two cases reduced the EII from the range of 5346-7452 lx to 436-1144 lx at row 1 while at row 2, the reduction is from 2220-2999 lx to 253-616 lx. Furthermore, for the same row in June and December, the amount of illuminance was reduced from the range of 1962-35729 lx to 187-3539 lx which is equivalent to a reduction of 90%. Hence, the integration of VB helps to shade the harsh direct lighting that penetrates the room through the window opening. VB7 showed the least efficiency with a reduced range of 9.7-65.6% at rows 1-4.

For rows 9-12, generally, the EII was reduced although there were some cases which showed the same or increased values compared to the base case. On average, VB4, VB5, and VB6 showed the least reduction with 4%, 12%, and 19% respectively. This shows that there is a decline in lighting quantity that comes from the window opening due to the VB efficiency of blocking direct lighting into the interior. Hence, in this portion of the room, it is recommended to conduct office works that do not require more lighting such as computer work and photocopy work. Additional electrical lighting can be added to the rear space to increase the illuminance level. The overall EII was higher in December each time when compared to March and June. The base case and VB3-7 achieved the recommendation of 300-500 lx level in that particular month.

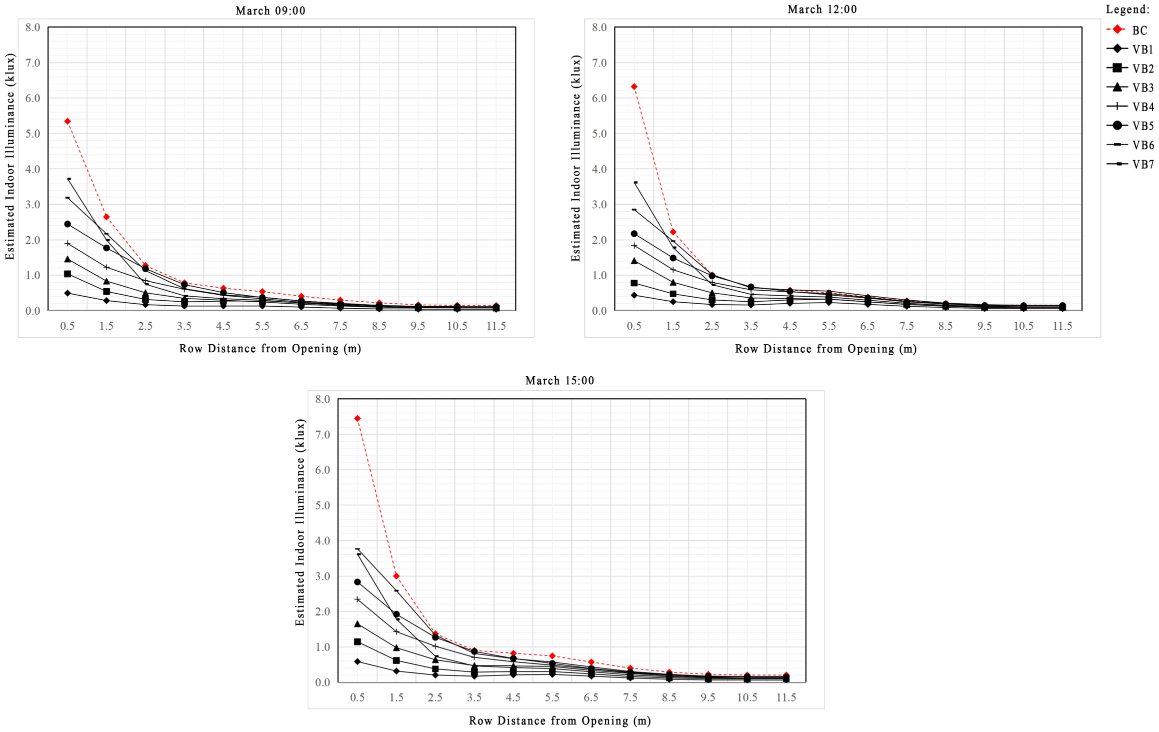


Fig. 5. Estimated indoor illuminance performance of base case and VB cases for 21st March

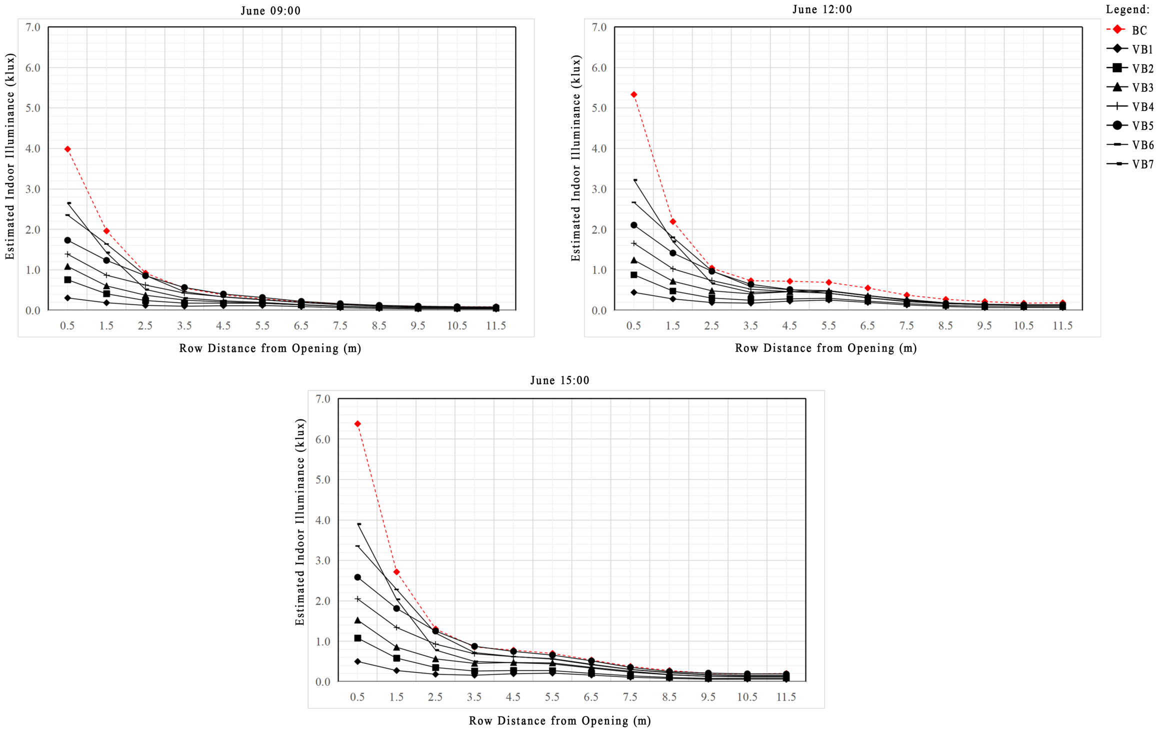


Fig. 6. Estimated indoor illuminance performance of base case and VB cases for 22nd June

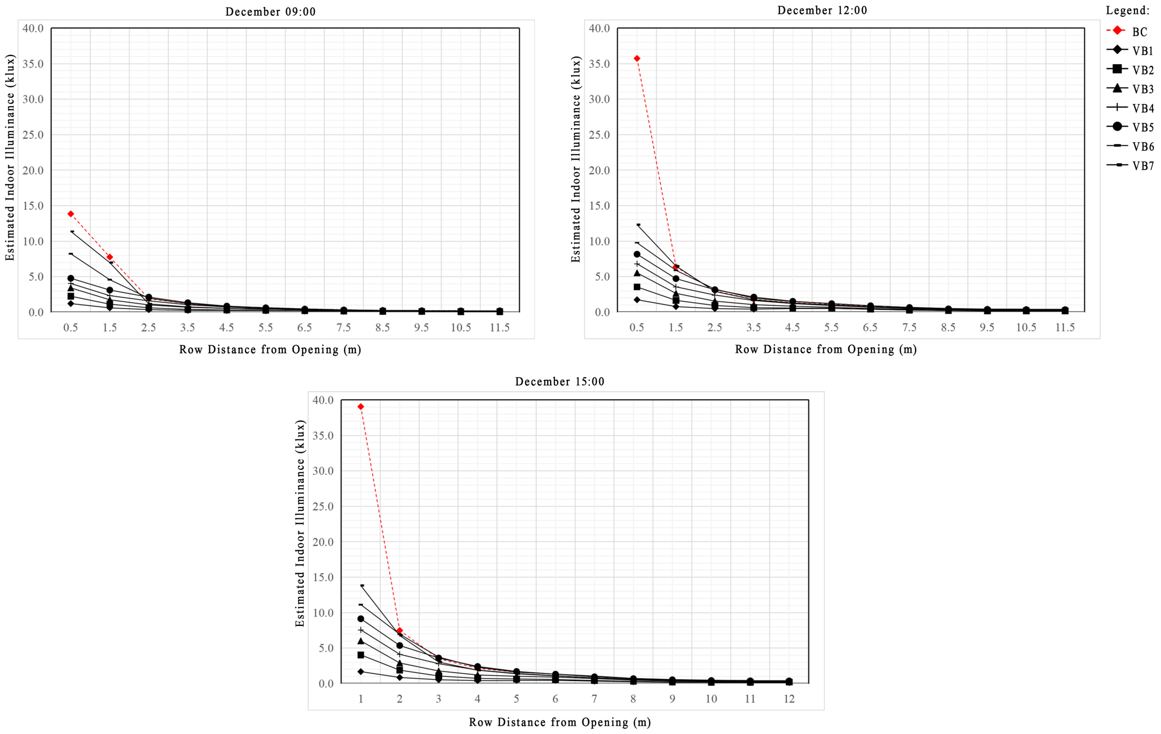


Fig. 7. Estimated indoor illuminance performance of base case and VB cases for 22nd December

Figures 8 and 9 show the percentages of work plane illuminance ratio that meet the benchmark of $E_{min}/E_{max}>0.5$ and $E_{min}/E_{max}>0.7$ [27]. Generally, all the cases increased the percentage of meeting the benchmark when compared to the base case. VB5 showed the best performance which achieved 100% for the former benchmark. VB4 also attained 100% for March and June while being the second highest in December with 99.21%. VB4 and VB5 also demonstrated the best performance (54.51-89.68%) by topping seven (7) out of nine (9) timings for the latter benchmark. The other two cases were VB1 and VB2 which were highest in December, at 900 (84.92%) and 1500 (85.71%), respectively. The results show that the integration of VB and LP is able to give a more uniform daylight distribution when compared to a room installed with LP only.

VB4 and VB5 showed the overall best performance among the eight (8) cases. The integration of both cases with LP creates better daylight uniformity across the deep, office room. This is caused by the angle of the VB which helps in blocking the direct light from the exterior while behaving as a surface reflector to illuminate the middle and rear portion of the room. Though both VB4 and VB5 are not the best cases for DF and EII (Rows 1-4), they improved the interior illuminance level when compared to the base case while achieving optimum daylight distribution across the room.

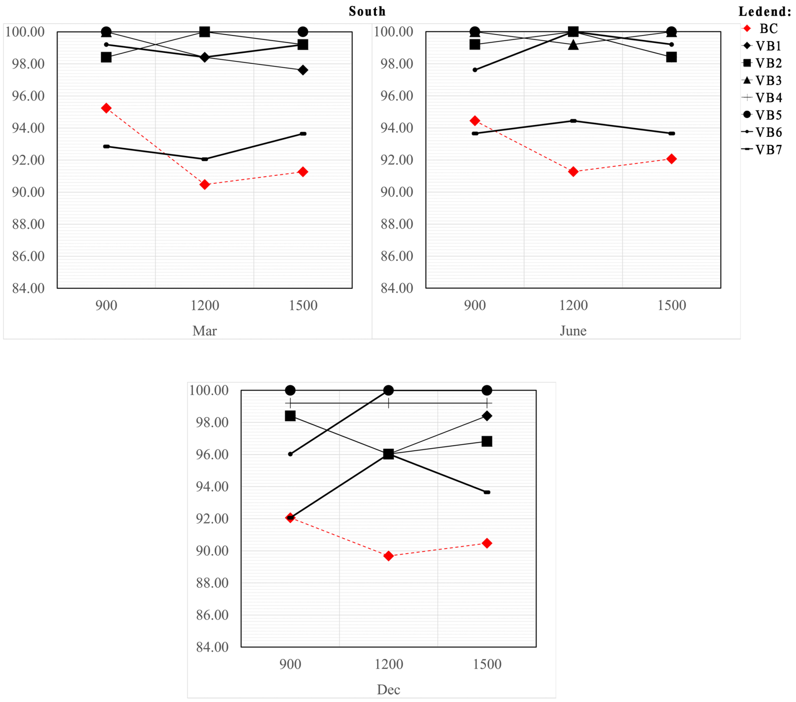


Fig. 8. Percentages of the work plane illuminance ratio that meet the benchmark of 0.5 (South)

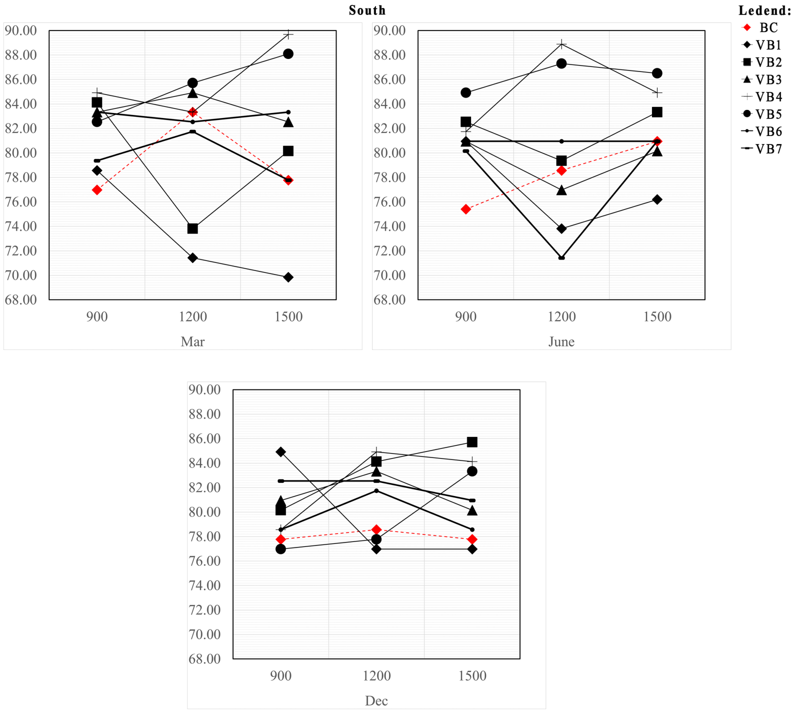


Fig. 9. Percentages of the work plane illuminance ratio that meet the benchmark of 0.7 (South)

4. Conclusions

The integration of VB to a horizontal LP is a feasible method to enhance daylight performance in a deep, open-plan high-rise office building in a tropical climate. While the LP illuminates the deep interior of the area, the addition of the VB allows for lower illumination from the intense lighting at the window opening and hence, creates a better daylight distribution across the room when compared to a room with LP only. It also helps in creating a better lighting environment for office workers. The VB4 and VB5, with the blind angle of 0° and -15° were suggested as the ideal complement to LP. This makes it possible for building designers to utilise natural illumination, which reduces power usage, as opposed to artificial lighting. High-rise office building can implement the integration of VB and LP system to make the building more sustainable and thus, reduces the use of non-renewable energy resources.

Further study on human responses through questionnaires, full-scale experiments, energy calculations, and temperature studies can be done to enhance the robustness of this integrated system.

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