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Daylight Performance of Integrated Horizontal Light Pipe with Shading Devices (Validation) for High-Rise Building in Tropical Climate

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ABSTRACT

Daylight is known to bring benefits to human in terms of productivity, psychology, and physiology. The emergence of deep plan layout in high-rise hinders the utilisation of the abundance daylight available in tropical climate. This brings challenges to ensure a uniform distribution in the interior room. This study focuses on the software validation of the integration of a horizontal light pipe (LP) and shading devices (SD) to illuminate the deep plan where the former provides daylight in the deepest portion of the room while the latter helps to shade the excessive daylight at the window opening. The shading devices that have been chosen are overhang, light shelf, and blinds. The computer simulation, Integrated Environment Solution: Virtual Environment (IESVE), is being validated with physical model experiment with a scale of 1:10. The experiment was conducted in an open carpark in Universiti Sains Malaysia, Penang, Malaysia from 9am to 3pm for two days. The validation was done using graph comparison, Pearson Correlation, relative root mean square error (RRMSE), and relative mean bias error (RMBE). The results shows that the daylight ratio (DR) from the software has positive relationship with the experiment data. Hence, the software can be used to further simulate various integration of LP and SD.

1. Introduction

Tropical climate possesses a great opportunity for daylight harvesting due to its nature of having an abundance of daylight throughout the day [1,2]. The benefits of having daylight in the interior had been well known such as increasing the productivity of office workers, creating better indoor environment, reducing electrical consumption, and promoting human psychology and physiology [3,4,5,6,7].

Due to the current rise of deep plan layout especially in office buildings to maximise the floor area, a light distribution system has to be implemented to harvest the daylight. One of the effective light distribution systems is light pipe (LP) [8,9,10]. LP helps to illuminate the deep interior of a room. However, although the rear portion of the room is being illuminated, the front portion receives an excessive amount of light which will cause visual discomfort or a non-uniform distribution across the

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interior [11]. Hence, there is a need for the inclusion of shading device (SD) to achieve a good daylight utilisation in the room where the presence of SD alone leaves the deep interior being too dark under illuminated. Furthermore, studies which use Integrated Environmental Solutions: Virtual Environment (IESVE) as their software also focus on LP and SD separately [3,12,13,14,15,17]. Hence, study on the integration of horizontal LP with SD is essential to provide a uniform distribution of daylight in a deep plan office layout. This paper focuses on the initial validation of IESVE through scaled model experiment of horizontal LP and SD integration before conducting further simulation.

2. Methodology

2.1 Scaled Model Experiment Setup

There are several methods used in daylighting study such as full-scale modelling, scaled model experiment, mathematical calculations, and computer software. Due to time and cost constraints, this study employs scaled model experiment to validate IESVE software.

Both the experiment and IESVE model which consists of the integrated LP with shading devices are built identically. For the scaled model, based on previous case studies on typical high-rise open plan office configuration, a model room of 6.0m (width), 12.0m (depth), and 2.7m (height) was constructed in a scale of 1:10 [17]. The dimension of the model is shown in Figure 1. The room has a window to wall ratio of 55% where it is a typical percentage for a room in its category [15]. There are three types of SD used for this experiment which are overhang, light shelf, and blinds (Figure 2). These SD are chosen as they are the most widely used SD according to previous study [12,13,14]. The material and reflectance of the interior wall, ceiling, floor, LP, and the shading devices surfaces in the room are shown in Table 1, where the values are accordance to Illuminating Engineering Society standard [18].

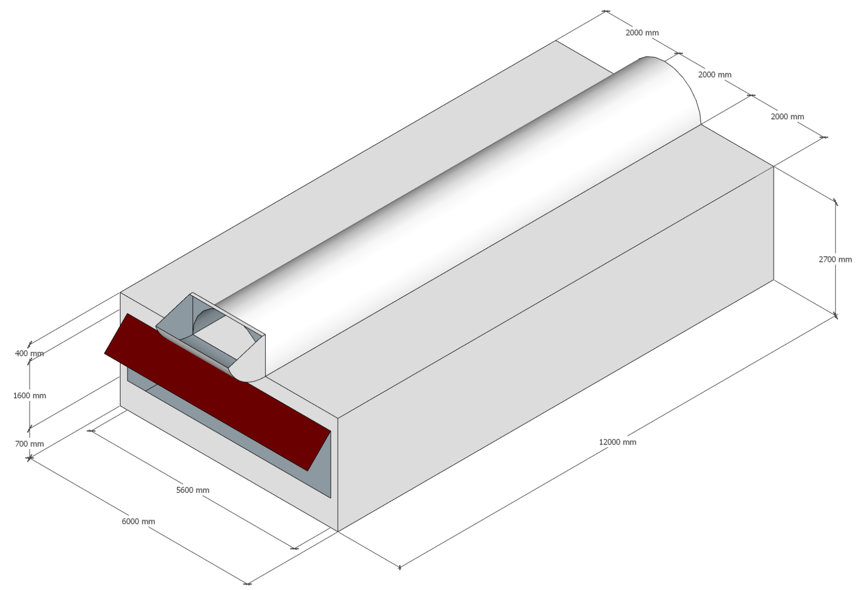

Fig. 1. Actual scale model with dimensions

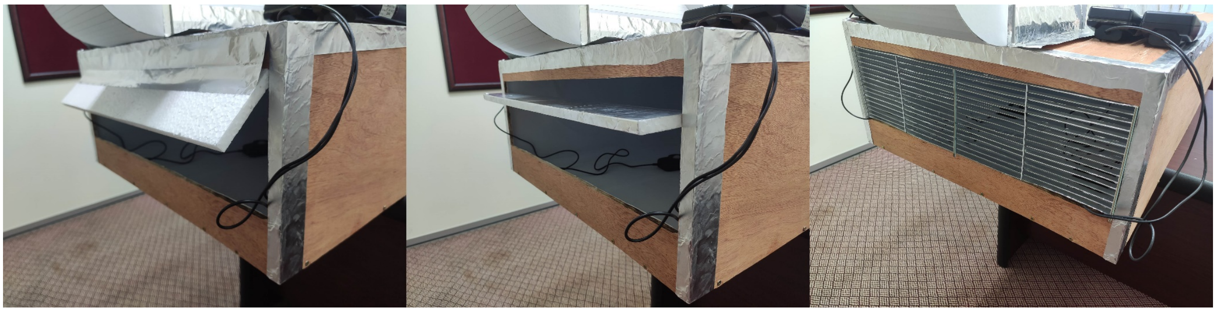

Fig. 2. Scaled shading device of overhang, light shelf, and blinds

Table 1
Surface properties for each element

Surface	Reflectance (%)	Specularity (%)	Roughness Value	Type
Wall	67.7	0.03	0.03	Plastic
Floor	67.7	0.03	0.20	Plastic
Ceiling	67.7	0.03	0.03	Plastic
LP	72.2	0.05	0.03	Metal
LS	72.2	0.05	0.03	Metal

The model was placed in an open car park in Universiti Sains Malaysia, Penang, Malaysia with a latitude of 5° 21′ N and longitude of 100° 17′ E. The site was chosen as it is an unobstructed area with no shading interference from nearby building or vegetation as shown in Figure 3 (Panoramic view). The orientation of the model was South as Penang is located slightly above the Equator to obtain more daylight duration throughout the day. The experiment was conducted for two days on 3rd and 4th May 2022 to ensure the reliability of the data.

There were four probes (Hanna's HI 97500) used in the experiment as shown in Figure 4. One of the probes was used to obtain the outdoor illuminance while the other three probes were placed inside the model with a distance of 400mm from one another (Figure 5). Figure 6 shows the whole physical model set up for the experiment. The readings were recorded manually and taken hourly from 9am to 3pm while interchanging between the three shading devices.

Fig. 3. Experiment site panoramic view

Fig. 4. Instrumentations for physical scaled model experiment

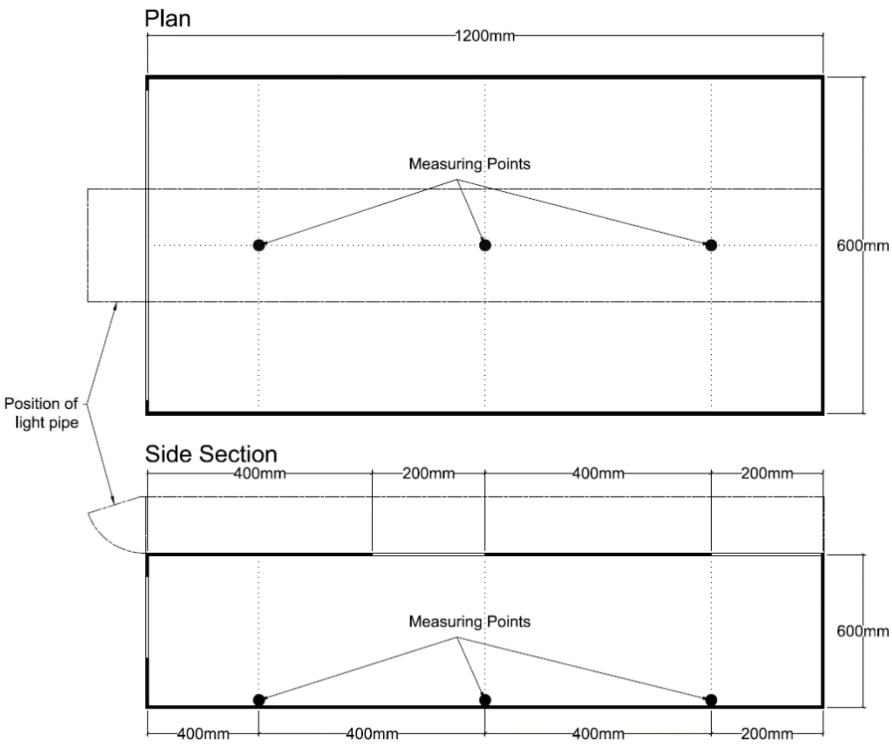

Fig. 5. Plan and side elevation of the physical scaled model experiment

Fig. 6. Physical scaled model experiment set up

2.2 Computer Simulation Setup

The experiment scaled models were built in IESVE using ModelIT function albeit in the scale of 1:1. The same function was also used to create the other components such as the LP, and three type of shading devices. Through the Radiance function in the software, respective surface reflectance based on the scaled model experiment (Table 1) were assigned. The sky condition was set to CIE intermediate Sky with Sun while the date was set to 3rd May. As the experiment was conducted in Penang, Bayan Lepas was set in the simulation as it is the nearest to the site. The 'Illuminance-working plane' option was used throughout the simulation with a height of 0.8m.

2.3 Criteria of analysis

Daylight ratio (DR) is used to assess the validity of the software as it is more reliable than absolute illuminance value. This is due to the differences between the simulation sky models and tropical sky [11]. The calculation of DR is shown in Equation 1.

$$Daylight\ Ratio = \frac{Indoor\ Illuminance}{Outdoor\ Illuminance} \quad (1)$$

Besides DR, this study uses Pearson Correlation, relative root mean square error (RRMSE), and relative mean bias error (RMBE) to determine the validity, viability, and readability of the data from experiment and simulation (Equation 2, 3, and 4).

$$Pearson\ Correlation = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (2)$$

$$Relative\ Root\ Mean\ Square\ Error = \sqrt{\frac{1}{n}\sum\frac{(x-y)^2}{n}} \quad (3)$$

$$Relative\ Mean\ Bias\ Error = \frac{1}{n}\frac{\sum(x-y)}{n} \quad (4)$$

where *n* is the number of data, *x* is the experiment data, and *y* is the simulation data.

3. Results and Discussions

The DR for both IESVE and the two experiment dates is shown in Figure 7. Generally, the DR of IESVE showed a similar pattern to the experiment data. The former showed relatively lower DR than the latter. For the overhang SD, the IESVE DR tends to show a lower DR from both the experiment data when comparing to the LS and blinds. There are also some differences between both the experiment data such as at 2pm for the 3 SD. This is caused by the differences in the sky condition when the readings were taken on both days. The DR for IESVE and all the SD, especially LS, showed the most similarity between 9am-11am.This may be influenced by the angle of the sun when entering and reflecting into the model.

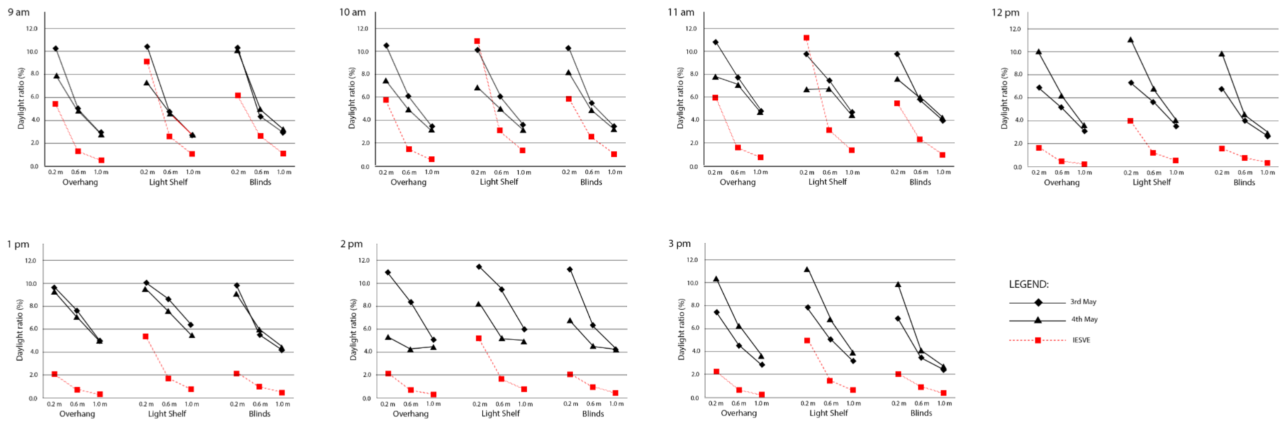

Fig. 7. DR of IESVE and both experiment data for overhang, light shelf, and blinds

Table 2 shows the statistical comparison between both experiment dates (3rd and 4th May 2022) and simulation data. There is a total of 42 readings that were taken for both days for each shading device. The Pearson Correlation results for the overhang, light shelf, and blinds for both days were 0.80, 0.82, and 0.83 respectively. The results showed that the simulation software data was reliable as the value was almost equal to 1.00. It also proved that there is a significant positive linear relationship between both data.

The RRMSE values were 28.99%, 11.21%, and 25.92% for overhang, light shelf, and blinds respectively while 24.98%, 13.96%, and 21.89% were the value for the RMBE calculation. Although there is no available guideline or standard for the two statistical indicators, previous study has recorded 32.00% and 20% for RRMSE and RMBE [19]. Reinhart and Breton [20] recorded 110% and 39% while McNeil and Lee [21], showed a RRMSE of 23% and RMBE of 13%. Therefore, the calculated RRMSE and RMBE for overhang, light shelf, and blinds are comparatively reliable as the percentages are within the range of the previous study (RRMSE 23-110% and RMBE 13-39%).

Table 2
Statistical comparison between IESVE and experiment data for overhang, light shelf, and blinds

	Overhang	**Light Shelf**	**Blinds**
Pearson Correlation	0.80	0.82	0.83
RRMSE	28.99	11.21	25.92
RMBE	24.98	13.96	21.89

4. Conclusion

This study also demonstrated the credentials of using scaled model as compared to full scale model as it shows a good similarity in terms of reflectivity of light on smaller scale surface when comparing to the IESVE software. This supports the outcome of several previous studies using scaled model [22,23]. However, the use of scale model has its limitation where user's experience test cannot be conducted due to the smaller scale.

This paper concludes that IESVE simulation can be used to simulate LP with SD such as overhang, LS, and blinds. However, only the value of DR can be used instead of the absolute value from the simulation. This is due to the underestimate of the IESVE outdoor illuminance value when comparing to the actual outdoor illuminance of a tropical sky as discussed in Section 3. The DR comparison of the software and experiment showed positive relationship (average Pearson Correlation of 0.81) between both sets of data and therefore, proved that IESVE can be used to further simulate various integration of LP and complex SD variables such as different rotation angle and size to determine the optimum configuration that provides uniform distribution in a deep plan office building.

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