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Validation of IES-VE for Assessing Daylight Performance of Building Implementing Horizontal Light Pipe and Shading Systems in the Tropics

Feny Elsiana[1, 3], Sri Nastiti N Ekasiwi [2, a)] and IGN Antaryama[2]

[1]*Doctoral Student, Department of Architecture, Institut Teknologi Sepuluh Nopember, Indonesia, 60111*
[2]*Department of Architecture, Institut Teknologi Sepuluh Nopember, Indonesia, 60111*
[3]*Department of Architecture, Petra Christian University, Indonesia, 60236*

[a)] *Corresponding author: nastiti@arch.its.ac.id*

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Abstract. Various daylight simulation tools, which are rapidly developed, become a reliable way for simulating the complex daylighting environment. Empirical validation of the daylight simulation tool is essential in determining its reliability, especially in simulating light transport and shading system in the Tropics. Distinct from previous research, the validation involves Horizontal Light Pipe (HLP), a side window with shading systems in different room aspect ratios and orientations. This study aims to validate the simulation results of Integrated Environmental Solutions-Virtual Environment (IES-VE) Radiance IES with the measurement results of physical scaled models for evaluating HLP, light shelves, and blinds' daylight performance under intermediate and overcast sky conditions. Two physical scaled models 1:10 represent office rooms with HLP and shading systems with different room aspect ratios were constructed. Daylight Factor (DF) and Daylight Ratio (DF) of physical scaled model measurement and IES-VE simulation were compared. The results showed that under intermediate and overcast sky conditions, the Pearson correlation between simulation and measurement results using DR and DF was strong, significant, and positive, as high as 0.84 and 0.80, respectively. The Mean Bias Error between simulation and measurement results under intermediate and overcast sky conditions were -12% and -7.7%, respectively. IES-VE is reliable to evaluate the HLP and shading systems' daylight performance with different room orientations in the Tropics.

INTRODUCTION

Daylight use in the building brings benefits for energy use, occupant productivity, and health. A proper daylighting strategy in the building can reduce the energy use for electric lighting, peak electric demands, and cooling [1]. Daylighting also improves the occupants' performance [2], subjective mood, attention, and alertness [3]. The use of daylight offers the most consistent and fullest color spectrum for the human eye [4].

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Many office buildings have a deep plan design, considering the spatial requirement of the workplace and economic reasons [5]. Deep plan building design limits the area that can access daylight. The daylight intensity reduces as the distance from the side window increases [1].

Classified as a light transport system, Horizontal Light Pipe (HLP) can distribute daylight to the area distance from the side window. HLP consists of aperture, pipe, and opening distribution [6]. Aperture collects, redirects, and in some cases concentrates or collimates the incident light flux [7]. Pipe transports and opening distribution then distribute daylight to the deep zone of the building.

The potential for daylight utilization in the Tropics is high [8], including the integration of HLP as a daylighting strategy. In the Tropics, HLP should be combined with shading systems [6] to decrease the excessive daylight level at the area adjacent to the side window [9]. HLP with shading systems, consisting of partial blinds and internal light shelves are studied.

Many daylighting performance studies of HLP and shading systems employ simulation as a tool. Those studies including simulation with Radiance and Opticad [7]; Radiance v.3.6 [10]; IES-VE [6,8,9,11]; Radiance-based simulation software [12, 13].

Various daylight simulation tools, which are rapidly developed, become a reliable way for simulating the complex daylighting environment [14]. 54% of those simulation tools are Radiance-based because Radiance has experienced extensive validation [15]. Radiance, a highly accurate physically based backward ray-tracing software, uses the raytracing calculation method [8].

Integrated Environmental Solutions-Virtual Environment (IES-VE) can perform building performance analysis and dynamic energy simulation. IES-VE are Radiance based which considers surface reflection, transmission, and refraction values [9]. Classified as a combined model method where the design tools and Building Performance Software are in the same environment (Fig.1), IES-VE gives possibilities for the operator to control model precision within all steps of model production, manipulation, and simulation [16]. IES-VE is also an unbiased simulation tool, which does not perform systematic errors to the approximation [15].

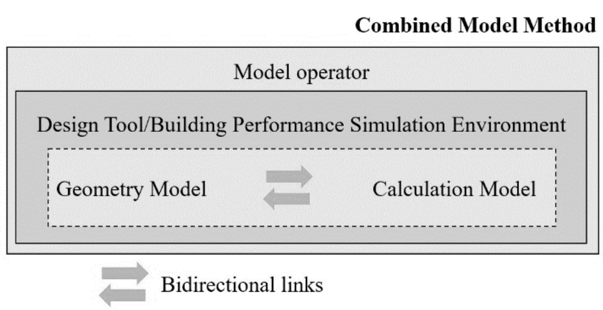

FIGURE 1. Combined model method [16]

Simulation tools must be tested and validated against the measurement of built reality, experimental tests, or other validated tools, including in the Tropics. Empirical validation was conducted, considering that IES-VE employs International Commission on Illumination (CIE) sky models to set up the global illuminance which is different from sky condition in the Tropics [8].

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Simulating a tropical sky condition is challenging, because of a higher global illuminance than CIE sky models in simulation tools.

Empirical validation of IES-VE in previous research employed side window strategy with a coating layer [17]; Horizontal Light Pipe [9]; Anidolic Daylighting System [11], and Light Shelf [8]. The validation is conducted by comparing simulation results against onsite measurements in the classroom [17], and physical scaled model 1:10 [8,9,11].

Distinct from previous research, the validation involves Horizontal Light Pipe (HLP), a side window with shading systems in different room aspect ratios and orientation. This study aims to validate the simulation results of IES-VE Radiance IES with the measurement results of physical scaled models for evaluating HLP, light shelves, and blinds' daylight performance under overcast and intermediate sky conditions.

METHODOLOGY

Two physical scaled models 1:10 represent office rooms with HLP and shading systems with different room aspect ratios were constructed for validation purposes. Physical scaled model 1:10 is selected to consider detailed refinement of spatial elements and study precisely both direct and diffuse daylight penetration [18]. Validation is conducted by comparing IES-VE simulation results with measurement results. The relationship between simulation and measurement results was analyzed using Pearson Correlation. The discrepancy between measurement and simulation results are also calculated using Mean Bias Error (Equation 1) and Relative Mean Bias Error (Equation 2) [19].

$$\mathrm{MBE} = \frac{1}{n}\sum(\mathrm{ir} - \mathrm{ie}) \quad (1)$$

$$\mathrm{MBErel} = \frac{\mathrm{MBE}}{\bar{\mathrm{ie}}} \quad (2)$$

where:

n is the number of readings

i_r is the reading using IES-VE

i_e is the measured data from physical scaled models

$\overline{ie}$ is the mean of the measured data from physical scaled models

Physical Model Description and Simulation

Room A had 6 m in width, 2.7 m in ceiling height, and 10 m in depth. Room B had a 7.5 m in width, 2.7 m in ceiling height, and 8 m in depth. The aspect ratio of rooms A and B were 0.6 and 0.94. The physical scaled models 1:10 were constructed using plywood. The interior surface of the model was painted, with reflectance values 0.45 for the floor, 0.75 for the ceiling and wall. Table 1 showed physical scaled models' configuration, while Table 2 showed the material properties of physical scaled models.

Both rooms had a side window with a window-to-wall ratio of 67%. The side window has 0.9 m in sill height and 1.8 m in window height. The glazing material of the window was clear glass 5 mm with visible transmittance (VT) of 0.88. The internal light shelf is constructed using mirror

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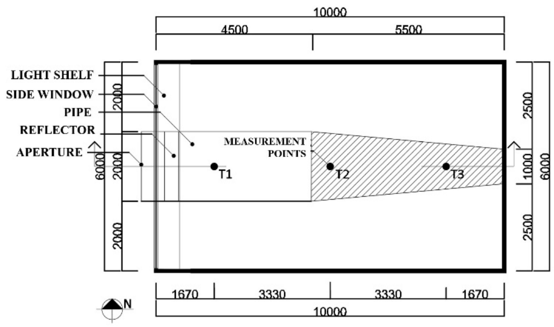
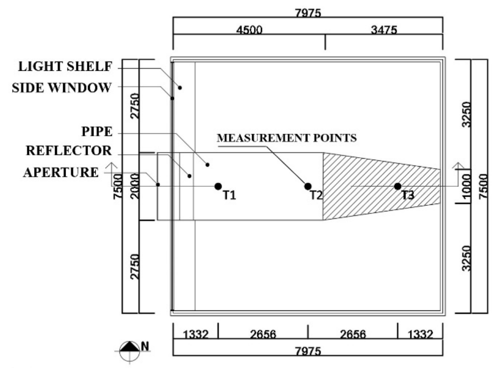
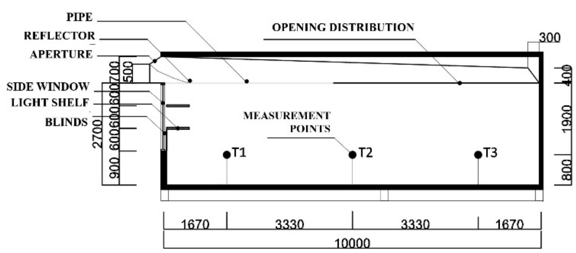
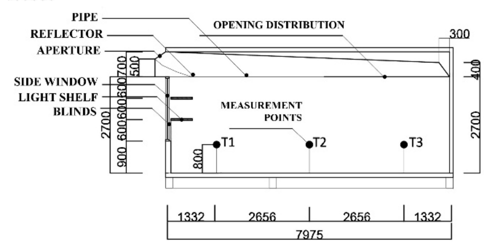
acrylic for its upper surface and painted white with reflectance 0.75 for its lower surface. The light shelf had 0.6 m in width. The blinds were constructed using plastic models and has a reflectance value of 0.4 (Table 2). The blind slats had an inclined angle of 45º and were located at 0.9 m to 1.5 m above the floor.

TABLE 1. Configuration of two physical scaled models

	Office Room A	**Office Room B**
Plan		
Section		

The dimension of HLP in room A was 2 m in width and 10.3 m in length. The dimension of HLP in room B was 2 m in width and 8.3 m in length. In the back of both rooms, the HLP was tapered and had 1 m in width. The material of the aperture was clear glass and had a VT of 0.88. The internal surfaces of HLP were covered by mirror acrylic with a reflectance value of 0.85. The aperture was directed to the East/West, following the best orientation of HLP in the Tropics [21].

TABLE 2. Material properties of physical scaled model and IES-VE

Element		**Material Properties**	
		Physical Model 1:10	**IES-VE**
Room	Floor	Light grey painted, reflectance 0.45	Plastic: Light grey, reflectance 0.45
	Ceiling	White painted, reflectance 0.75	Plastic: white paint, reflectance 0.75
	Wall	White painted, reflectance 0.75	Plastic: white paint, reflectance 0.75
Window	Clear glass	Visible transmittance (VT) 0.88	Glass VT 0.88
Light shelf	Shelf (upper surface)	Reflectance 0.88	Metal, reflectance 0.88
	Shelf	White painted, reflectance 0.75	Plastic: white paint, reflectance 0.75
Blinds	slat	Reflectance 0.40	Plastic, reflectance 0.40

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Horizontal Light Pipe	Pipe Interior Surface	Reflectance 0.85	Metal, reflectance 0.85
	Aperture	VT 0.88	Glass VT 0.88
	Opening Distribution	VT 0.88	Glass VT 0.88
	Reflector	Reflectance 0.85	Metal, reflectance 0.85

Three HOBO data logger U12-012 were installed to measure illuminance level at each room, every hour. The position of measurement points and HOBO U12-012 are represented in Table 1 and Fig.2. HOBO Pendant data logger UA-002-64 was employed to measure outdoor illuminance level. Material reflectance for ceiling, wall, and floor was measured using Light Meter HIOKI Lux Hi tester 3423. Measurements of daylight level were conducted at the 7th roof deck at P building, Petra Christian University, Surabaya (altitude 7°38’ S, longitude 112°79’ E) (Fig.3).

(a) (b)

FIGURE 2. The interior of physical scaled models (a) room A (b) room B

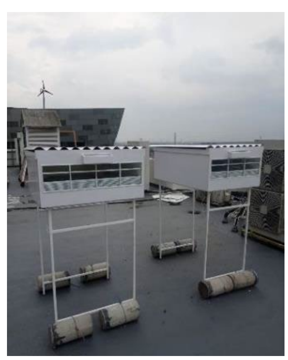

FIGURE 3. Placement of physical scaled models at rooftop P Building Petra Christian University

Two models of office rooms were constructed in IES-VE and had the same surface reflectance values, configurations, sky condition, and measurement times as the physical scaled model (Table 2). The simulation uses the climate data of Juanda International Airport, the nearest area to the measurement location. Table 3 showed the measurement time, under intermediate and overcast

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sky conditions. Table 4 showed the radiance parameters employed in this study, following the previous research about HLP by Kwok and Chung [10].

TABLE 3. Measurement time

Measurement	Date	Time	Sky Condition	Orientation
1	25 February 2021	09.00-15.00	Overcast	West
2	18 March 2021	11.00, 13.00-15.00	Overcast	West
3	19 April 2021	09.00-15.00	Intermediate	East
4	22 April 2021	09.00-15.00	Intermediate	East

TABLE 4. Radiance parameters

Parameter	Abbreviation in Radiance	In accordance with Kwok and Chung, 2008 [10]	Range [20]				
			Min	Fast	Accurate	Very Accurate	Max
Ambient bounces	-ab	5	0	0	2	5	8
Ambient accuracy	-aa	0.2	0.5	0.2	0.15	0.08	0
Ambient resolution	-ar	64	8	32	128	512	0
Ambient divisions	-ad	2048	0	32	512	2048	4096
Ambient super samples	-as	512	0	32	256	512	1024

Daylight Performance Assessment

The relative ratio should be used for daylight simulation validation in the Tropics considering the substantial difference between simulated outdoor illuminance under CIE skies and measured outdoor illuminance under sky conditions in the tropics [13]. Daylight Ratio (DR) and Daylight Factor (DF) were employed to assess the daylight performance under the intermediate sky and overcast sky, respectively (Equation 3). Previous studies in the Tropics also employed DR which is suited for areas near the equator [8, 9].

$$DF \text{ or } DR = \frac{Ei}{Eo} \, x \, 100\% \tag{3}$$

where
DF is Daylight Factor, under overcast sky condition
DR is Daylight Ratio, under intermediate sky condition
Ei is Illuminance indoor, measured at work plane 0.8 m height from floor (lx)
Eo is Illuminance outdoor (lx)

RESULTS AND DISCUSSION

The DR for various times at rooms A and B for each measurement point are presented in Fig 4. In general, Daylight Ratio measurement results with the physical scaled models are in line with IES-VE simulation results. Under intermediate sky conditions on 19 and 22 April, the DR pattern

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of simulation results and measurement results have the same trend. The highest DR level achieved at 09:00 decreased at 10:00-12:00 and then increased at 13:00-15:00. In general, the DR level resulting by measurement is slightly higher than by simulation, except for measurement point T1 (near the perimeter window) at 09:00-10:00, in both rooms A and B.

The measured and simulated DF for various times at rooms A and B for each measurement point are presented in Fig 5. In general, Daylight Factor measurement results with the physical scaled model are in line with IES-VE simulation results. Simulated DF levels were higher compared with measurement results at measurement point T1 (near the perimeter window). The DF level of two office rooms had the same pattern, which had the highest level near the side window then decreased as the distance from the side window increased. These results are in line with previous research by Heng et al. [9]. However, the application of HLP and shading systems reduced the average DF near the side window reached 5% and increased average DF at the area far from the side window reached 120% [6].

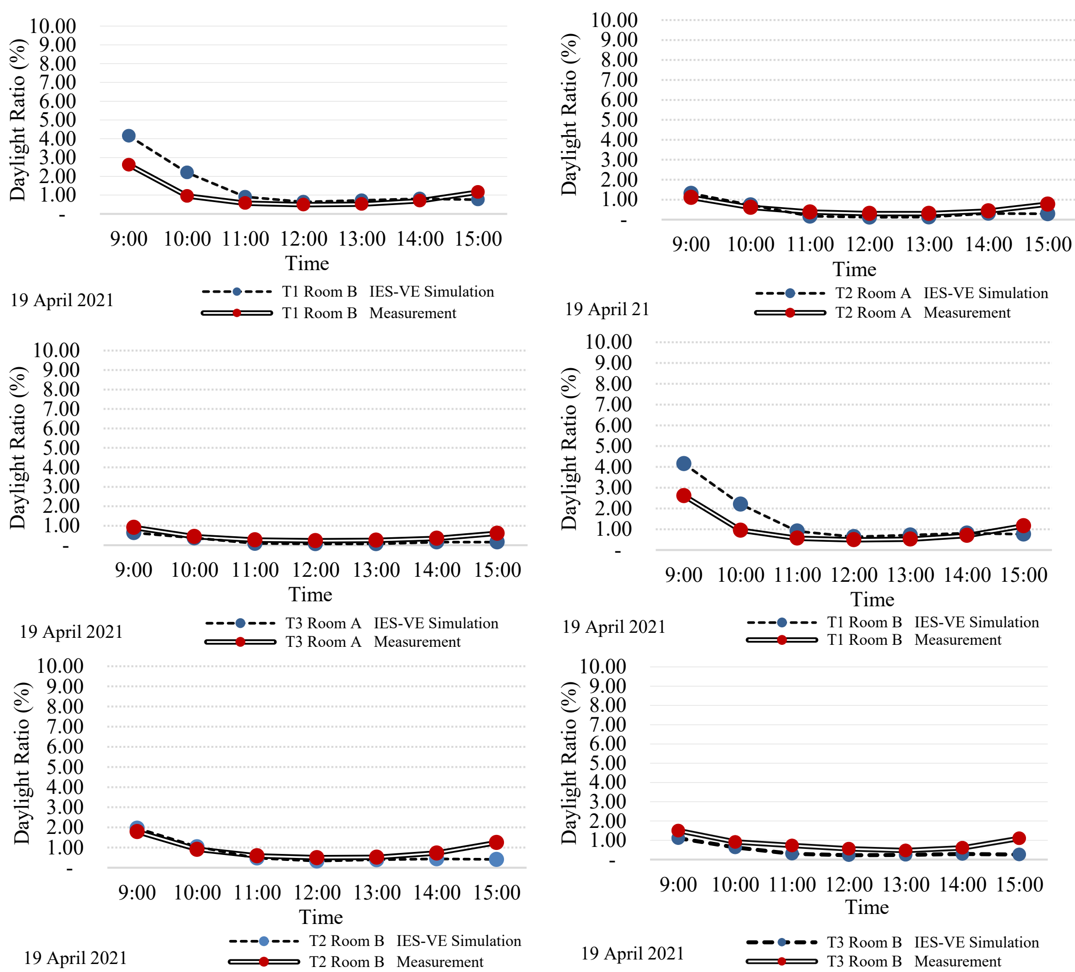

FIGURE 4. Daylight ratio of measurement and IES-VE simulation results under intermediate sky condition

TABLE 5. Pearson correlation between IES-VE simulation and measurement results

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Sky Condition			IES-VE simulation	Measurement
Intermediate		Pearson Correlation	1	.84**
	IES-VE simulation	Sig. (2-tailed)		.000
		N	84	84
		Pearson Correlation	.84**	1
	Measurement	Sig. (2-tailed)	.000	
		N	84	84
Overcast		Pearson Correlation	1	.80**
	IES-VE simulation	Sig. (2-tailed)		.000
		N	66	66
		Pearson Correlation	.80**	1
	Measurement	Sig. (2-tailed)	.000	
		N	66	66

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

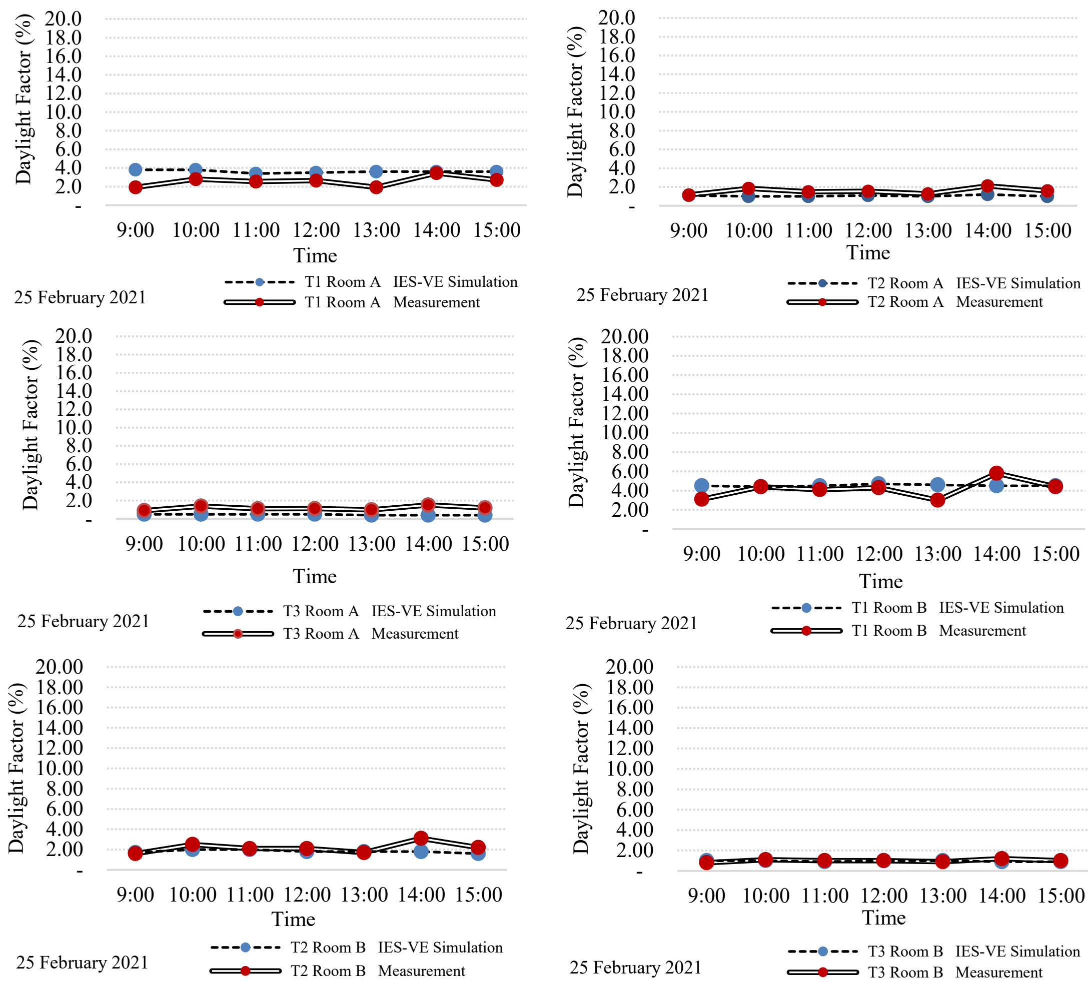

FIGURE 5. Daylight factor of measurement and IES-VE simulation results under overcast sky condition

Fig.6 showed the relationship of DR and DF between measurement and IES-VE simulation results for both rooms. The results showed a linear relationship between measurement and simulation results. A positive correlation also showed, where the higher DR/DF of measurement,

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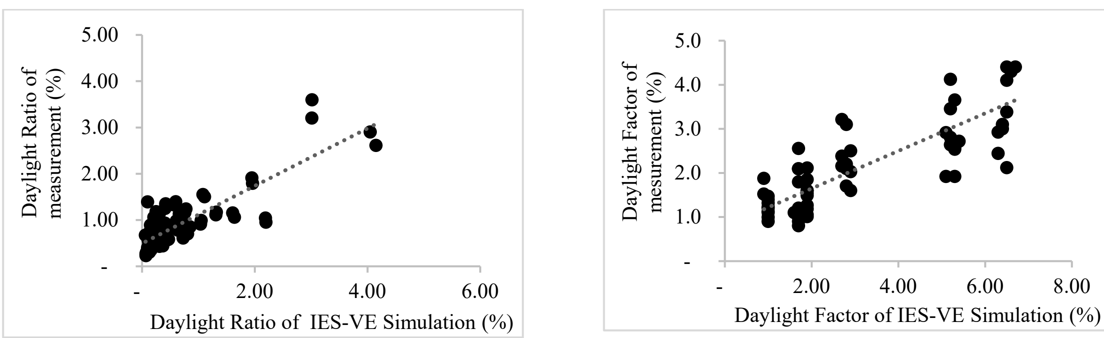
the higher DR/DF of simulation. Pearson Correlation between IES-VE simulation and measurement results under intermediate sky conditions are very high (0.84**), significant, positive (Table 5). Pearson Correlation between IES-VE simulation and measurement results under overcast sky conditions are very high (0.80**), significant, positive (Table 5). These results were in line with previous research by Heng et al. [9].

Under intermediate sky condition, the largest difference of DR between simulation and measurement occurred in T1 room B, on 22 April 09.00, as big as 1.54%. Under overcast sky condition, the largest difference of DF between simulation and measurement occurred in T1 room B, on 18 March 11.00, as big as 2.38%.

Comparing measurement to IES-VE simulation results also showed that the Mean Bias Error (MBE) value of intermediate sky condition was higher than the MBE value of overcast sky condition. MBE value under intermediate and overcast sky conditions were -12% and -7.7%, respectively (Fig.7). The relative MBE of the intermediate and overcast sky conditions were -13.7% and -3.6%, respectively. Negative MBE means a tendency of IES-VE simulation to underestimate both Daylight Ratio and Daylight Factor. These values were less than 20% [22] and showed that IES-VE is one of the reliable daylight simulation tools to analyse the HLP, light shelf, and blinds' daylight performance in the Tropics using Daylight Factor than Daylight Ratio.



(a) (b)

FIGURE 6. Daylight ratio and daylight factor of measurement and IES-VE simulation results under (a) intermediate sky condition an (b) overcast sky condition

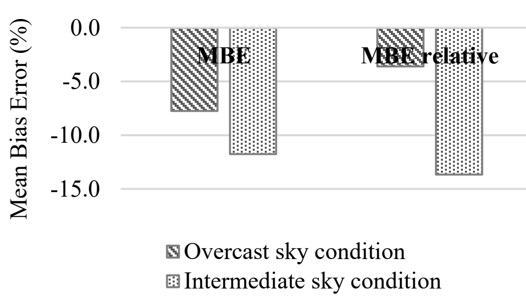


FIGURE 7. Mean Bias Error and Relative Mean Bias Error under intermediate and overcast sky conditions

CONCLUSION

In general, Daylight Ratio and Daylight Factor measurement results with the physical scaled models were in line with IES-VE simulation results. Pearson correlation of simulation and

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measurement results was positive, significant, and very high, as high as 0.84 for intermediate and 0.80 for overcast sky conditions. The Mean Bias Error (MBE) under intermediate and overcast sky conditions were -12% and -7.7%, respectively. The relative MBE of intermediate sky and overcast sky conditions were -13.7% and -3.6%, respectively. The results showed that IES-VE is one of the reliable daylight simulation tools to analyze the Horizontal Light Pipe, light shelves, and blinds' daylight performance in the Tropics using Daylight Ratio and Daylight Factor.

Future research can employ different radiance parameters to assess the accuracy of IES-VE simulation results. A longer period of measurement has to be conducted, to study dynamic daylight performance, such as Useful Daylight Illuminance, Daylight Autonomy.

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