Empirical Validation of Daylight Simulation Tool with Physical Model Measurement

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Abstract: Problem statement: In recent years, daylighting simulation tools have been increasingly used by many architects, engineers and researchers to evaluate the day lighting performances of building design. Most of these tools employ CIE sky models for simulation. However, the accuracy and applicability of these tools for tropical sky are doubtable. The aim of this study was to validate the computer simulated result with scaled physical model results measured under real tropical sky. **Approach:** Daylighting model was constructed using scaled physical model to be tested under real sky measurement. The same model was configured in Desktop Radiance 2.0 to perform day lighting simulation experiments. All the measurements were carried out under intermediate and overcast tropical sky conditions in Malaysia; while related CIE sky conditions were used for simulations. **Results:** Due to the CIE sky conditions are very dissimilar from the actual tropical sky; simulated absolute value results such as external illuminance, absolute work plane illuminance and surface luminance recorded high mean differences from the measured results, with 81.63; 71.06 and 49.71%, respectively. However, relative ratios such as Daylight Factor (DF) yielded mean difference of 26.06% and luminance ratio was 29.75% only. The average mean difference was 44.37%. **Conclusion/Recommendations:** To compare the performances, relative ratios such as DF and luminance ratio showed better accuracies. For future research, validation on other parameters can be performed such as orientations, angle of the overhang, glazing, window sizes, colors, environment settings and electric lighting.

Key word: Daylight, simulation, desktop radiance, physical model

INTRODUCTION

The developments in windows technologies have provided new possibilities for architects to utilize daylight for indoor climate and visual comfort (Dubois, 2001; Arasteh *et al*., 2003). Daylight not only contributes to energy saving for building lighting, but also provides a healthy and comfort environment for the occupants. Since 30-50 percent of energy used in a commercial building is to illuminate the interior spaces, daylight can reduce the dependency on electrical lighting (Robbins, 1986). For the same amount of light, daylight is more efficient at providing light in comparison to electric lighting and producing less heat. Thus, daylight has become a commonly used design strategy for better building performance. However, in tropical climate, the abundance of daylight has not yet been utilized (Ossen *et al*., 2005).

Since last 30 years, increasing numbers of daylight simulation tools are made available (Ander, 2003; Loutzenhiser *et al*., 2007; Xia *et al*., 2008). Pre-design stage is the best opportunities for improving a building's energy performance. During this stage, simulation tools are useful to predict and improve building daylight design (Lim *et al*., 2008). Besides, simulation tools are also utilized to assist in the lighting and shading system control in buildings (Mahdavi, 2008).

Radiance is an advance lighting analysis and visualization tool for a UNIX environment. Desktop Radiance 2.0 is a more user-friendly derivative of Radiance that runs under the Windows operating system from within AutoCAD 14 using pull-down menus. However, not all of the key operating features in standard Radiance are available in Desktop Radiance 2.0 (Mistrick, 2000).

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Desktop Radiance 2.0 uses International Commission on Illumination (CIE) sky models for simulation: CIE clear sky, CIE intermediate sky and CIE overcast sky and uniform sky. Sky model influences the distribution and amount of external illuminance to further predict the indoor illuminance. Thus, the accuracy of using CIE skies to simulate buildings under tropical sky is debatable (Zain-Ahmed *et al*., 2002; Linhart *et al*., 2010).

The aim of this study is to validate the simulated and measured results using Desktop Radiance 2.0 to the result of the scaled physical model experiment under real tropical sky. Besides, it is also to test the daylight performance of the simulation tool for various variables.

MATERIALS AND METHODS

Model configuration: A room with a single aperture was developed according to the geometries and characteristics of Malaysian office (Ossen *et al*., 2005). As shown in Fig. 1, the physical model of an office room was constructed using 12 mm thick plywood with 1: 2 scales. The geometrical configurations were as shown in Fig. 2. An aperture without glazing was constructed on the east external wall. The Window-to-Wall Ratio (WWR) of the aperture was 50%. The whole model was painted in white. The test site was located at an open car park at Faculty of Built Environment, University Technology Malaysia, Skudai, Johor, Malaysia. The same model configuration was developed in Desktop Radiance 2.0 for the simulation study. The location used for the simulation was Johor Bahru, with latitude 1°28' 0"N and longitude 103° 45' 0"E.

Limitation: The surrounding environment of the site may affect the daylight performances. Thus, the reflectance value of the surrounding environment and the model surface were measured and modeled. The average reflectance value for the tar surface of the car park was 0.05; whereas the white painted model surface was 0.87. However, there were vegetations adjacent to the physical model not modeled for simulation. Hence, the effect in term of providing shade was negligible.

Fig. 1: Installation of scaled physical model on selected site

Experiment procedure: Three Reference Points (RP) were taken at work plane height 1 ft. 6 in. (450 mm): RP_1 (4 ft./1200 mm from the aperture, center of the room), RP_2 (7 ft. 7 in./2275 mm from the aperture) and RP_e (external illuminance), as shown in Fig. 3. Measurements of the 3 reference points were taken concurrently in order to calculate Daylight Factor (DF). Equipments used were Light Meter LX-100 (range 0-20000 lux) for indoor illumination and Photometer IL1400A (range 0-200000 lux) for external illuminance (Fig. 4).
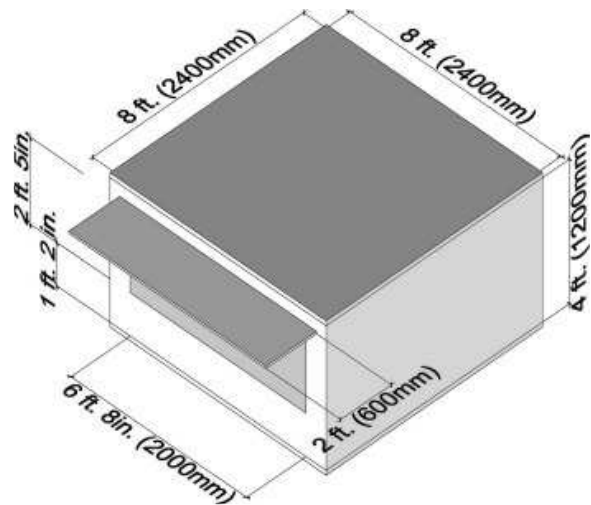

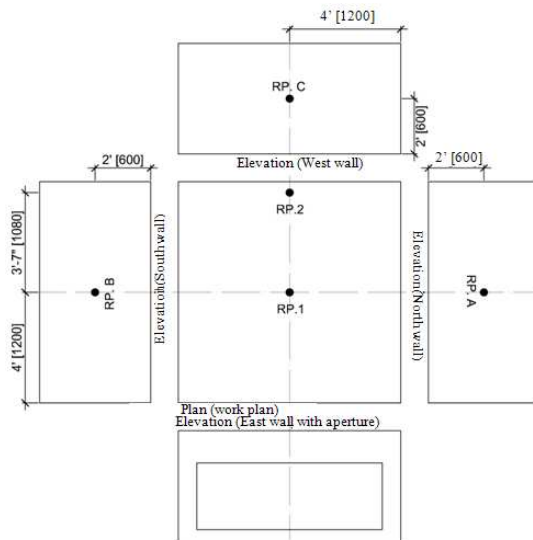Fig. 2: Model for field measurement and computer simulation with scale 1:2

Fig. 3: Reference points for illuminance and luminance measurement

Table 1: Summary of test cases for field measurement and Desktop Radiance 2.0 simulation

Test case	Date	Time	Sky Condition	Orientation	Overhang
Field measurement					
Measured 1	17 Nov 2009	0915-0925	Overcast	East	No
Measured 2	17 Nov 2009	0925-0935	Overcast	East	600 mm
Measured 3	17 Nov 2009	1215-1225	Intermediate	East	No
Measured 4	17 Nov 2009	1225-1235	Intermediate	East	600 mm
Measured 5	17 Nov 2009	1445-1455	Intermediate	East	No
Measured 6	17 Nov 2009	1455-1505	Intermediate	East	600 mm
Computer simulation					
Simulation 1	17 Nov 2009	0915	CIE Overcast	East	No
Simulation 2	17 Nov 2009	0925	CIE Overcast	East	600 mm
Simulation 3	17 Nov 2009	1215	CIE Intermediate	East	No
Simulation 4	17 Nov 2009	1225	CIE Intermediate	East	600 mm
Simulation 5	17 Nov 2009	1445	CIE Intermediate	East	No
Simulation 6	17 Nov 2009	1505	CIE Intermediate	East	600 mm

Fig. 4: Light Meter LX-100 (left) and Photometer IL1400A (middle), Luminance Meter Topcon BM9 (right)

Luminance Meter Topcon BM9 (Fig. 4) was used to measure the surface luminance. Three Reference Points (RP) were taken at the centre of the surfaces of the three internal walls: RP_A (north wall), RP_B (south wall) and RP_C (west wall) as shown in Fig. 3.

Criteria of analysis: In order to validate the various performances of Desktop Radiance 2.0, several experiments were carried out:-

External illuminance (E_e): was measured and simulated for comparison in order to have a better understanding of the tropical sky and CIE sky characteristics.

Absolute Work Plan Illuminance (WPI): were measured and simulated at RP_1 (e_1) and RP_2 (e_2) for comparison as shown in Fig. 3. According to MS 1525: 2007 (Department of Standards Malaysia, 2007), the recommended minimum absolute WPI for general office is 300 lux.

DF: is defined as the ratio of interior illuminance on a horizontal surface (E_i) to the exterior illuminance on a horizontal surface (E_e) (Robbins, 1986). Only the measurements taken under overcast sky (test 1 and 2) were applicable for DF analysis

$$DF = (E_i/E_e) \times 100 \tag{1}$$

Absolute surface luminance: of RP_A (L_A), RP_B (L_B) and RP_C (L_C) were recorded for comparison.

Luminance ratio: is calculated as the ratio of one surface luminance value (L_1) to the adjacent surface luminance value (L_2). Luminance value of RP_A (L_A) was used as a reference value to compare with luminance value of RP_B (L_B) and RP_C (L_C):

$$R1 = L_A / L_B \tag{2}$$

$$R2 = L_A / L_C \tag{3}$$

Test cases: All tests were summarized in Table 1. Since this experiment intended to compare the measured and simulated results, all the tests were conducted only on east orientation. For further comparison, external overhang was employed to test the effect of overhang on the daylight performance. Hence, two cases were configured for each test: Without overhang and with 600 mm overhang.

RESULTS

Illuminance experiment: The measured external luminance under real tropical sky in Malaysian outdoor condition was much higher in comparison to the simulated data under CIE standard sky. Figure 5 shows that the highest external luminance was at the noon time (Test 3). The highest difference between the measured and simulation result was Test 6, (92.43%); whereas the closest between the measured and simulation was Test 1 (69.17%). External illuminance varies drastically during the experiment.

The external luminance directly influenced the absolute WPI. Therefore, the measured absolute WPI was also much higher than the simulated. As shown in Fig. 6, the measured results had all the reference points in the 6 tests fulfilled the minimum 300 lux recommendation. However, for the simulated results, only 25% fulfilled the recommendation. The highest difference between the two results was Test 3 RP1 (87.29%); while the lowest was Test 2 RP2 (41.39%). The mean difference was 71.06%.
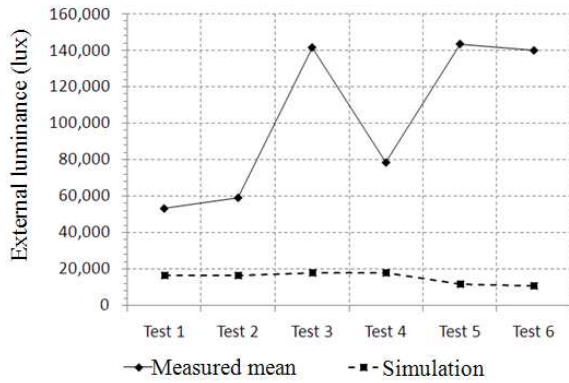
Fig. 5: Comparison of measured and simulated external illuminance
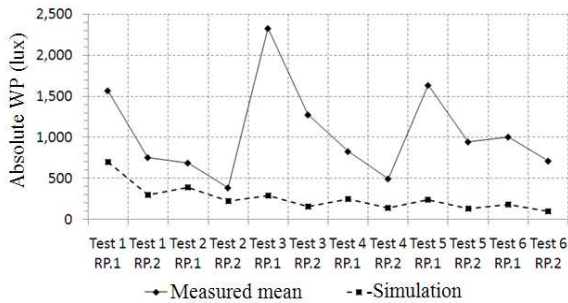

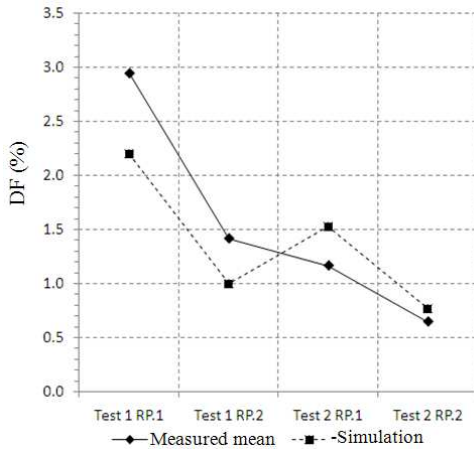
Fig. 6: Measured and simulated absolute WPI

Fig. 7: Measured and simulated DF

Simulated DF result was close to the measured results (Fig. 7). The highest difference from the measured results was Test 2 RP1, 30.77% higher; while the lowest was Test 2 RP2, 18.46% higher. The mean difference was 26.06% higher.
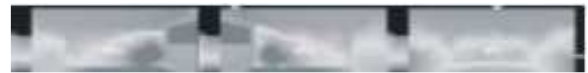

Fig. 8: Luminance false color for simulation 1

Fig. 9: Luminance false color for simulation 2

Fig. 10: Luminance false color for simulation 3

Fig. 11: Luminance false color for simulation 4

Fig. 12: Luminance false color for simulation 5

Fig. 13: Luminance false color for simulation 6

Luminance experiment: The Desktop radiance luminance false color for simulation 1-6 are shown in Fig. 8-13. The distribution of the colors shows the uniformity of the surface luminance. Glare occurred in Simulation 1 (Fig. 8) because the contrast of the surface luminance was drastic due to the direct sunlight patch through the east facing aperture. With the use of 600 mm overhang in Simulation 2, the direct sunlight patch was reduced and gives a more uniform distribution of daylight (Fig. 9). During noon and afternoon time (Simulation 3-6), the direct sunlight patch was not obvious except in Simulation 5. In all cases, the floor was brighter while the ceiling was darker. It also showed that RP_A was always brighter than RP_B and RP_C; while RP_C was brighter than RP_B.

Due to the higher external luminance, the measured absolute surface luminance was higher than the simulated (Fig. 14). The highest differences of the simulated from measured results was Test 3 RP_A, yielded 79.13% lower; while the lowest was Test 2 RP_B, with 3.62% higher. The mean difference was 49.71% lower.
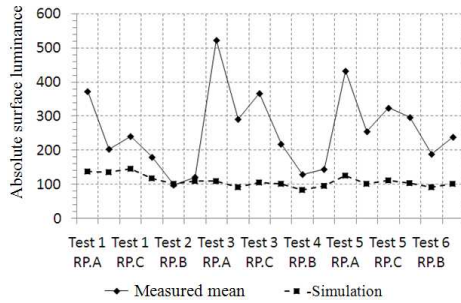
Fig. 14: Measured and simulation results for absolute surface luminance; test 1-6
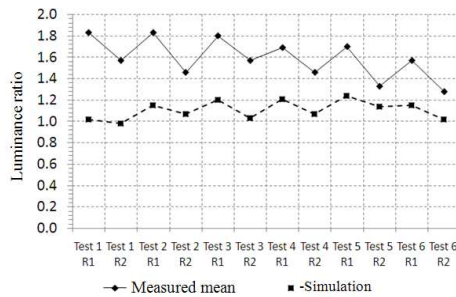

Fig. 15: Measured and simulation results for luminance ratio; test 1-6

Figure 15 shows the differences between the measured and simulated luminance ratio for R1 (RP_A/RP_B) and R2 (RP_A/RP_C) for all test cases. Generally, it shows that R_1 was constantly higher than R2 for both measured and simulated results ($RP_A > RP_C > RP_B$). The highest difference of the simulated results from the measured was Test 1 R_1 (44.26% lower) and the lowest was Test 5 R2 (14.29% lower). The mean difference was 29.75% lower.

DISCUSSION

The simulation tool was unable to predict external illuminate close to the real Malaysian tropical sky condition. However, lower differences were recorded for simulation under CIE overcast sky (Test 1 and (2) in comparison to the CIE intermediate sky (Test 3-6). This is because the luminance distribution of the tropical sky during overcast sky is much more uniform.

Table 2 summarizes the differences of simulated results from measured results for various criteria. The high mean differences between the measured and simulated results in the external luminance, absolute WPI and absolute surface luminance conclude that it is inapplicable to use these simulation tools to predict the absolute luminance and luminance values. In order to simulate the daylight performance accurately, DF and luminance ratio are considered more comparable and reliable.

Table 2: Summary of the differences of simulated results from measured results

Criteria	Differences (%)		
	Min	Max	Mean
External illuminance	69.17	92.43	81.63
Absolute WPI	41.39	87.29	71.06
DF	18.46	30.77	26.06
Absolute surface luminance	3.62	79.13	49.71
Luminance ratio	14.29	44.26	29.75
Average			44.37

CONCLUSION

This study presents an empirical comparison between the scaled physical model measurement and Desktop Radiance 2.0 simulation daylight performance results. The average mean difference between the measured and simulated results was 44.37%. Due to the dissimilar characteristics between tropical sky and CIE sky models, relative ratios such as DF and luminance ratio are better choices to compare the performances. Factors that affect the accuracy of the performance in this study include the surrounding environment reflectance and landscape. For future research, validation on other parameters can be performed such as orientations, angle of the overhang, glazing, window sizes, colors, environment settings and electric lighting.

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