THE IMPLICATIONS OF SKY MODEL SELECTION FOR THE PREDICTION OF DAYLIGHT DISTRIBUTION IN ARCHITECTURAL SPACES

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ABSTRACT

This paper investigates the implications of the selection of various sky luminance distribution models for the computational prediction of daylight distribution in architectural spaces. The illuminance distribution in an actual test-space is simulated based on six different sky models, and the results are compared with illuminance measurements taken in the test space. The variations of simulation results and their relationship with the measurements are presented and discussed.

PROBLEM STATEMENT

In a separate study, the predictions of six sky luminance models were compared with actual luminance measurements obtained with a sky scanner in a tropical context (Lam et al. 1997). This paper explores the implications of the sky model selection for the prediction of illuminance distribution inside architectural spaces. Specifically, we seek to answer the following questions:

a) What variations in the simulated illuminance levels for a typical architectural space is to be expected as a result of using different sky luminance models?

b) Is the extent of this divergence significant in view of other uncertainties involved in the design and evaluation process (e.g., building description, validity of the daylight simulation program, etc.)?

c) What can be said of the relative performance of various sky luminance models given the available measurement results?

APPROACH

The Sky Luminance Models

Six models were considered for this study, namely:

1) CIE overcast sky (Hopkinson et al. 1966).
2) All weather sky model (Perez et al. 1993).
3) ASRC-CIE model (Littlefair 1994).
4) Brunger's model (Brunger 1987).
5) Kittler's model (Kittler 1986).
6) Perraudeau's model (Perraudeau 1988).

Simulations

The original program DSM (Mahdavi and Pal 1996, Mahdavi and Berberidou 1994) was used for the simulation of illuminance distribution in the test space.

DSM utilizes the three component approach (i.e., the direct, the externally reflected, and the internally reflected daylight component, to obtain the resultant illuminance distribution in buildings. The direct component is computed by numerical integration of the contributions from all of those discretized patches of the sky dome that are "visible" as viewed from reference receiver points in the space. External obstructions are treated by the projection of their outline from each reference point onto the sky dome and replacement of the relative luminance values of the occluded sky patches with those of the obstruction. A radiosity based approach is adopted for computing the internally reflected component. An earlier version of this program was compared to three other prediction tools and was found to provide reliable results (Mahdavi et al. 1993).

Simulations were performed for a fixed grid of points on the floor of the test space (cp. Figure 1). For the same time period, simultaneous measurements of indoor and outdoor illuminance levels were obtained.

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Test Space

An actual space (a living room in a multi-storey building in Singapore) was selected for simulations and measurements. A schematic plan of this test-space is given in Figure 1, which also includes the simulation/measurement grid.

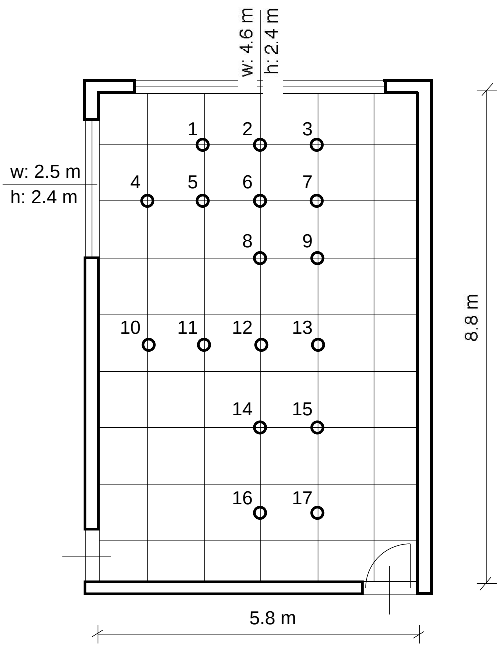

Figure 1: Schematic illustration of the test space and the location of the 17 reference points.

Reflectances (ρ) of the surfaces of this room as well as the transmittance (τ) of the fenestration were obtained based on spot measurements and were used as the input parameter for the simulation model (cp. Table 1).

Table 1: Input Parameters for Simulation Model

	ρ [%]	τ [%]
Fenestration	0.10	0.70
Walls	0.60	NA
Floor	0.70	NA
Ceiling	0.65	NA

Measurements

Indoor Measurements:
Continuous indoor measurements were performed over a period of three days for a selected number of points in the test space (cp. Figure 1). A total of 119 time-averaged (hourly) illuminance readings were used for the purpose of this study.

External Measurements:
To "calibrate" the sky luminance models for the simulation procedure, certain measured data (diffuse and global horizontal irradiance, as well as diffuse horizontal illuminance) are needed. These were obtained from the National University of Singapore radiometric and photometric measurement station in Singapore (Ullah 1996).

The sensors for the measurement of the illuminance and irradiance are placed on the roof of the lift shaft of a four storey building sited on the top of a ridge to maximize unobstructed views of the sky. Shadow rings are used to provide the diffuse horizontal illumination and radiation values. The measurements are taken and data stored on an hourly basis from 7 a.m. to 7 p.m. daily. The maximum, minimum, average and instantaneous hourly values are recorded.

RESULTS

Comparison of the Sky Models

Indoor illuminance levels for the reference points (cp. Figure 1) were computed for all six sky models using the aforementioned daylight simulation program (DSM). Based on these illuminance values, mean daylight factors (DF_m) were derived according to the following equation:

$$DF_m = \frac{1}{n}\left(\sum_{i=1}^{n}\frac{E_{p,i}}{E_{e,i}}\right)100 \ \ [\%] \qquad \text{eq. 1}$$

where

$E_{p,i}$ the simulated indoor horizontal illuminance level for point *p* at hour *i*

$E_{e,i}$ the simulated outdoor horizontal illuminance level for point *p* at hour *i*

n the number of (hourly) illuminance readings for point p

The results are shown in Figure 2, together with the daylight factors derived from illuminance measurements for the same points.

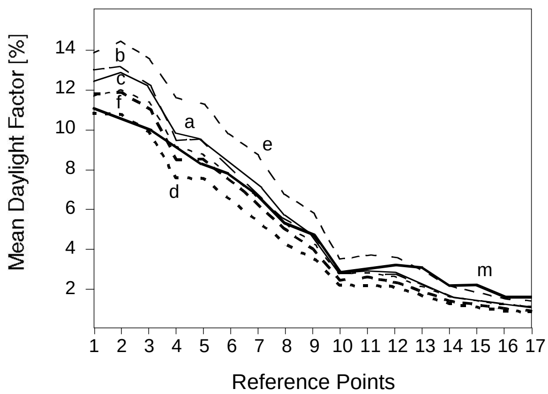

Figure 2: Mean simulated daylight factors for 17 reference points in a test room (cp. Figure 1) using six different sky models (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau, m: Measured).

Figure 3 includes the daylight factors averaged for all six models together with the corresponding standard deviations, as well as the measured results.

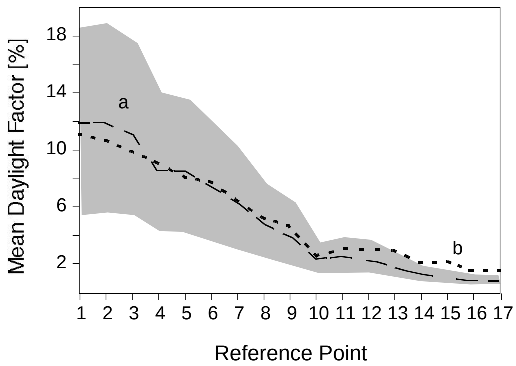

Figure 3: The predicted daylight factors (curve a) averaged over the six sky models with the corresponding standard deviations (the shaded zone). Also given is the measured average (curve b).

Comparison of the predictions and measurements

The relative error (RE) for the predictions of each sky model was calculated for each reference point according to the following equation:

$$RE = \frac{DF_{m,s} - DF_{m,o}}{DF_{m,o}} \; 100 \; [\%] \qquad \text{eq. 2}$$

where

$DF_{m,s}$ is the simulated mean daylight factor

$DF_{m,o}$ is the measured mean daylight factor

The results are shown in Figure 4.

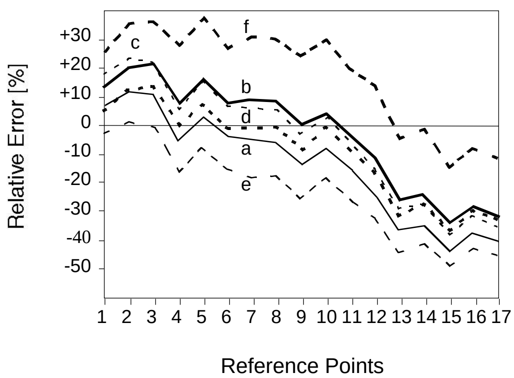

Figure 4: The relative errors of the six sky models in predicting the daylight factors for the 17 reference points in the test room. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau).

Figure 5 shows the mean of the relative errors with the corresponding standard deviations.

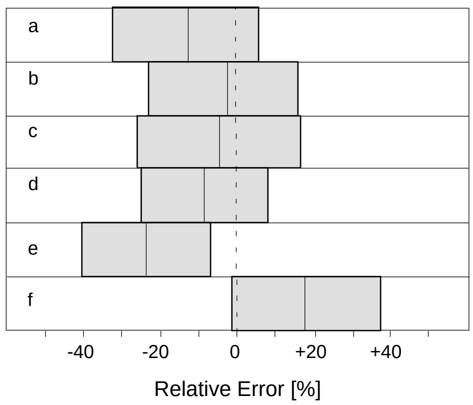

Figure 5: Mean Relative Errors with the Corresponding Standard Deviations. (a: CIE, b: Perez, c: Kittler, d: Brunger, e: ASRC-CIE, f: Perraudeau)

DISCUSSION

The following discussion of the results must be seen in the context of the following limitations and constraints:

- While the space selected for this study is quite typical for residential buildings, we do not imply that the results obtained for this space unconditionally apply to all spaces, independent of their geometry, photometric properties of the building components, and the building orientation.
- Parallel continuous measurements of indoor and outdoor illuminance levels could be carried out only for a rather short period of time.
- While DSM has shown to be a rather reliable prediction tool, factors such as uncertainties in the determination of the input data (geometry of space and apertures, photometric properties of the building components and elements) may lead to inaccuracies in prediction of illuminance levels. Based on prior experience, errors of up to ±12 % must be expected.
- The main purpose of this paper was to explore the divergence of predictions based on various sky models relative to each other. Thus the data in this paper on the prediction-measurement differences is not meant to be seen as the ultimate judgement concerning the performance of the sky models.

Having established this understanding, we proceed to answer the three questions stated in the problem statement:

a) While the sky models considered for this study display a remarkable agreement in terms of their overall trends, they clearly lead to divergent predictions of indoor illuminance levels in absolute terms (cp. Figure 2).

b) This divergence in predicted illuminance levels for the six sky models is not negligible. As Figures 2, 3, and 4 clearly demonstrate, the choice of a specific model does significantly affect the predicted illuminance levels. Here, "significance" is meant to imply that the errors caused by the prediction of a specific sky model may occasionally be of higher magnitude than those caused by the inaccuracies of the model itself (algorithmic limitations) or of the model input data (building description).

c) DSM's prediction of the trends in daylight distribution in the test space generally match the trend established by the measurements, independent of the sky model selected. However, the absolute values predicted do deviate to various extents from the measured results. According to the currently available measurement results, DSM predictions are closer to the measured values (particularly in the front portion of the test space) when Perez, Kittler, or Brunger model are used.

In conclusion, we would like to note that the combination of an advanced simulation model and a detailed sky model that would closely match the local sky luminance distribution patterns is very likely to provide the designer with reliable predictions of the daylight distribution in architectural spaces. More specifically, it is likely that the combined uncertainty in predictions of a detailed simulation tool and a reasonably accurate sky model (with a better local fit than the six models considered in this study) may not be critical if seen in the context of the uncertainties involved in the description of the geometry, materials, furnishing, and use patterns of interior spaces in the design phase.

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