A COMPARISON OF LUMINOUS EFFICACY MODELS FOR THE DIFFUSE COMPONENT OF SOLAR RADIATION

Sokol Dervishi[1, 2] and Ardeshir Mahdavi[1]
[1]Department of Building Physics and Building Ecology, Vienna University of Technology
Vienna, Austria
[2]Department of Architecture, EPOKA University, Tirana, Albania

ABSTRACT

To perform detailed architectural daylight analysis via simulation, appropriate sky models are needed. In the past, various sky luminance distribution models have been developed. Such models, however, require global and diffuse illuminance data for the relevant location. Measured data on global and – especially – diffuse external illuminance are available only for few locations. Hence, methods are needed that can derive from the more widely available irradiance data the corresponding illuminance data via reliable luminance efficacy models. In this context, the present paper focuses specifically on the problem of luminous efficacy models for the diffuse component of solar radiation. Toward this end, we comparatively evaluate several diffuse luminous efficacy models based on a database of measured diffuse illuminance and diffuse irradiance data from Vienna, Austria. These models typically involve mathematical formulations with multiple coefficients, whose values are derived for a specific location. The evaluation of the different models has been carried out considering all sky conditions from sunny, to partly cloudy, to overcast.

INTRODUCTION

Simulation-based architectural daylight analysis and design support requires information regarding external conditions. Specifically, prediction of daylight availability in indoor environments via computational simulation requires external global and diffuse illuminance data. As comprehensive measured external diffuse illuminance data is not available for most locations, approaches are needed to estimate horizontal diffuse illuminance based on more widely available diffuse irradiance data. Toward this end, the notion of diffuse luminous efficacy is typically applied, which denotes the ratio of diffuse illuminance to diffuse irradiance.

Several authors have suggested models to derive luminous efficacy for different sky conditions. Littlefair (1988), Aydinli and Krockman (1983) presented polynomial relations of different degrees using solar altitude as the only independent input variable for beam luminous efficacy. Another model, which also uses solar altitude as independent variable, was proposed by Robledo and Soler (2000). Littlefair (1988) established diffuse luminous efficacy as an interpolation between overcast and clear sky using sky clearness as an indicator. Using Littlerfair's model, Chung (1992) and Robledo et al. (2001) developed local luminous efficacy models (based on data from Hong Kong and Madrid, respectively) for overcast and intermediate skies. Perez et al. (1990) developed a luminous efficacy model for all sky types as a function of the solar zenith angle (Z), atmospheric precipitable water content (W), and the sky brightness index (Δ). The coefficients of these variables were specified as a function of sky clearness ranges.

The present work focuses on the comparison of six diffuse luminous efficacy models, aside from the option of using a single mean value of luminous efficacy, based on measured photometric and radiometric data obtained in Vienna, Austria.

APPROACH

The present research involves, from the method point of view, the following steps.

Measurements

The empirical basis of the model comparison was long-term measurements at the microclimatic monitoring station of the Department of Building Physics and Building Ecology (Vienna, Austria). Using a sky scanner, radiance and luminance is measured regularly (every 15 minutes) for 145 sky patches during the daylight hours, covering a variety of sky conditions, from sunny, to partly cloudy, to overcast. Given radiance and luminance values, horizontal diffuse irradiance and illuminance values were derived (Szirmay-Kalos 1999, Tregenza and Waters 1983).

The measurement period relevant for the models' test was from 01.08.2010 to 30.07.2011. Given the position of the measurement station, time intervals involving very low sun altitudes (less than 5 degrees) were excluded. Likewise, very low global horizontal irradiance values (less than 50 $W.m^{-2}$) were excluded, given the uncertainty in the sensor accuracy for this radiation intensity range. Parallel to radiometric and photometric measurements, a weather station at the same location monitored other external environmental parameter such as air temperature and air relative humidity. Table 1 shows the instrumentation specifications. The technical specification of the applied pyranometer and the meterogical weather station is shown in Table 1.

Table 1
Overview of the instrumentation specifications

Sensor	Information
Global and Diffuse irradiance (Sunshine pyranometer SPN1)	Overall accuracy: ±5% daily integrals, ±5% ±10 W.m² hourly averages ±8% ±10 W.m² individual readings Resolution: 0.6 W.m²=0.6 mV, range: 0 to > 2 000 W.m², sunshine status threshold: 120 W.m² in the direct beam, temperature range: -20 to +70 ° C, accuracy: Cosine Correction ±2% of incoming radiation over 0-90" Zenith angle, accuracy: azimuth angle ±5% over 360° rotation, Response time <200 ms
Monitoring weather station	Outdoor temperature: Absolute Error: < 0.3 K; Temperature range: -30 to +70 ° C; Response time < 20 s (≥ 1.5 m.s-1) Outdoor relative humidity: Absolute Error: < ±2%; Humidity range: 0 to 100 %; Response time < 10 s (≥ 1.5 m.s^{-1}) Wind speed: Absolute Error: <1%; Wind speed range 0 - 75 m.s^{-1}

Model selection

Aside from the option of using a single mean value of diffuse luminous efficacy (1D), six models were selected, namely Munner et al. 2000 (2D), Ruiz et al. 2001 first model (3D), Ruiz et al. 2001 second model (4D), Robledo and Soler 2001 (5D), Perez et al. 1990 (6D), Chung 1992 (7D) based on data obtained in Vienna, Austria. The selection of the models was based on their prior reported performance as well as the availability of required measurement data for model comparison. A brief summary of these models is provided below.

i. *Mean (constant) diffuse luminous efficacy (Model 1D)*

Based on the database of measured diffuse horizontal irradiance (G_d) and illuminance (E_d) levels, a local constant value, K_d for the diffuse luminous efficacy was derived as follows:

$$K_d = \frac{E_d}{G_d} \qquad (1)$$

ii. *Munner, Gul and Kubie Model (Model 2D)*

Munner et al 2001 used measurement data of five locations in UK to derive diffuse luminous efficacy as a function of clearness index k_t

$$K_d = 130.2 - 39.828 k_t + 49.975 k_t^2 \qquad (2)$$

iii. *Ruiz, Soler and Robledo First Model (Model 3D)*

Ruiz et al. (2001) derived a model of diffuse luminous efficacy (K_d) as a function of clearness index of diffuse radiation k_d. The correlation was obtained for Madrid.

$$K_d = 160.61 - 47.05 k_d - 196.94 k_d^2 \qquad (3)$$

iv. *Ruiz, Soler and Robledo Second Model (Model 4D)*

In this model, Ruiz et al. (2001) derived the diffuse luminous efficacy (K_d) as a function of solar altitude (α) and clearness index of diffuse radiation k_d.

$$K_d = 86.97 (\sin\alpha)^{-0.143} k_d^{-0.218} \qquad (4)$$

v. *Robledo and Soler Model (Model 5D)*

Robledo and Soler (2001) derived the diffuse luminous efficacy (K_d) as a function of sky brightness index Δ.

$$K_d = 91.07 \times \Delta^{-0.254} \qquad (5)$$

vi. *Perez et al. model (Model 6D)*

Perez et al. (1990) express diffuse luminous efficacy as a function of clearness of the sky (ε), atmospheric precipitable water content (W), solar zenith angle (z), and the sky brightness index (Δ), by the following equation:

$$K_d = a_i + b_i w + c_i \cos z + d_i \ln(\Delta) \qquad (6)$$

Here, a_i, b_i, c_i and d_i are coefficients corresponding to the clearness of the sky (ε) and are provided by the authors for eight ranges of the sky, variable from clear sky to overcast sky.

vii. *Chung model (Model 7D)*

Chung (1992) developed the diffuse luminous efficacy in Hong Kong during 1989-1991 based on the cloud ratio D (ratio of diffuse to global irradiance) as per equation 7.

$$K_d = 135.3 - 25.7 D \qquad (7)$$

Comparison

To evaluate the performance of the models the estimated diffuse luminous efficacy values were compared with the respective measured values using their respective original coefficients.

Three common statistical indicators were used for the comparison: the relative mean bias deviation MBD (Equation 8), the relative error RE (Equation 9), and the root mean square deviation RMSD (Equation 10).

$$MBD = \frac{\sum_{i=1}^{n}\left(\frac{M_i - C_i}{M_i}\right)}{n} \cdot 100 \quad (\%) \qquad (8)$$

$$MBD = \sum_{i=1}^{n}\left(\frac{M_i - C_i}{M_i}\right) \cdot 100 \quad (\%) \qquad (9)$$

$$MBD = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{M_i - C_i}{M_i}\right)}{n}} \cdot 100 \quad (\%) \qquad (10)$$

In these equations, M_i is the measured diffuse luminous efficacy, C_i is the computed diffuse luminous efficacy, and *n* the total number of pairs of diffuse irradiance and illuminance values.

RESULTS AND DISCUSSION

To compare the performance of the seven options, Figure 1 shows the percentage of the results (pairs of measured and calculated diffuse luminous efficacy levels) with associated maximum relative errors. Table 2 shows the same information numerically for discrete values of relative error (±10%, ±20%, ±30%, ±40%). Table 3 compares the seven options in terms of RMSD and MBD.

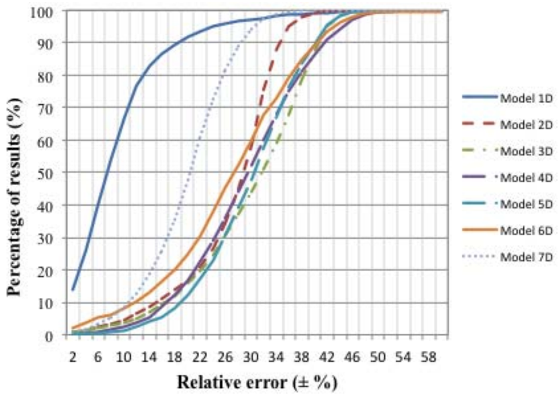

Figure 1 Percentage of the results (pairs of measured and derived diffuse luminous efficacy values) with respective maximum relative error (RE) for the seven options

Table 2
Percentage of results with corresponding maximum relative error (RE) for the seven models

MODEL	10%	20%	30%	40%
1D	66.8	66.8	97.1	99.1
2D	4.5	4.5	58.4	99.3
3D	3.7	3.7	43.9	87.5
4D	2.7	2.7	52.2	86.6
5D	1.4	1.4	47.9	89.9
6D	8.0	8.0	60.1	89.4
7D	8.0	8.6	94.3	99.9

Table 3
MBD and RMSD results for measured and calculated diffuse luminous efficacy values for the seven options

MODEL	MBD [%]	RMSD [%]
1D	-13.3	41.8
2D	-17.1	51.1
3D	-17.6	49.7
4D	-16.3	47.9
5D	-13.7	50.6
6D	-11.5	47.2
7D	-11.5	47.2

A visual inspection of the results warrants a number of conclusions: Diffuse luminous efficacy models do not “transport” well. All models provide data that significantly deviate from the measurements. As data shown in Figure 1 as well as Tables 2 and 3 illustrate, the simple constant diffuse luminous efficacy model performs significantly better than the other – more detailed – models, whose original coefficients were obtained for other locations. The Perez et al. 1990 model in the version with its original coefficients, even though intended to function as general model of diffuse luminous efficacy, does not perform satisfactorily for Vienna data. We could not find a systematic relationship between model errors and the intensity of global horizontal irradiance.

CONCLUSION

We compared several models of the diffuse luminous efficacy to derive horizontal diffuse illuminance values from the more widely available measured diffuse horizontal irradiance values. The comparison was conducted using detailed measurement data from Vienna, Austria. The results suggest that the original versions of the models do not perform well for Vienna data, including the one, which has been proposed to function as a globally applicable model.

We currently study the possibility of developing more robust (globally applicable) diffuse luminance efficacy models. Moreover, we are further exploring the validity of global luminous efficacy models for vertical (or any tilted) surfaces toward reliable derivation of incident illuminance levels.

REFERENCES

Aydinli S, Krochman J. 1983. Data on daylight and solar radiation. Draft for CIE TC, 4,2.

Chung TM. 1992. A study of luminous efficacy of daylight in Hong Kong. Energy and Buildings, Vol. 19,pp: 45-50.

Kasten A. 1966. A new table and approximate formula for relative optical air mass. Arch Meteorol Geophys Bioklimatol Ser B, Vol. 14, pp: 206–23.

Littlefair PJ.1988. Measurements of the luminous efficacy of daylight. Lighting Research and Technology, Vol. 20, pp: 177 -188.

Munner T, Kinghorn D.1997. Luminous efficacy of solar irradiance: improved models. Lighting Research and Technology, Vol. 29,pp: 185.

Muneer T, Gul MS, Kubie J. 2000. Models for estimating solar radiation and illuminance from meteorological parameters. J Sol Energy Eng, Trans ASME;Vol. 122,pp: 146–53.

Perez R, Ineichen P, Seals R, Michalsky J, Stewart R. 1990. Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy, Vol. 44,pp: 271-289.

Robledo L, Soler A. 2000. Luminous efficacy of global solar radiation for clear skies. Energy Conversion and Management, Vol 4,pp: 1769.

Robledo L, Soler A. 2001. On the luminous efficacy of diffuse solar radiation. Energy Convers Management, Vol. 42, pp: 1181–90.

Robledo L, Soler A, Ruiz E. 2001. Luminous efficacy of global solar radiation on a horizontal surface for overcast and intermediate skies. Theoretical and Applied Climatology, Vol 69, pp:123- 134.

Ruiz E, Soler A, Robledo L. 2001. Assessments of Muneer's Luminous Efficacy Models in Madrid and a proposal for new models based on his approach. Journal of Solar Energy Engineering, Vol. 123, pp: 220-224.

Szirmay-KalosL. 1999.Monte-Carlo methods in global illumination.Institute of Computer Graphics, Vienna University of Technology.

Tregenza P. and Waters I. M. 1983. Daylight coefficients. Lighting Research and Technology. Vol. 15 (2), pp: 65 – 71.

Wright J, Perez R, Michalsky J. 1989. Luminous efficacy of direct irradiance: variations with insolation and moisture conditions. Solar Energy, Vol. 42, pp: 387-394.