AN EMPIRICALLY-BASED ASSESSMENT OF COMPUTATIONAL SKY LUMINANCE DISTRIBUTION MODELS

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ABSTRACT

Simulation can support the design and operation of buildings for optimal thermal and visual performance. Specifically, the design and configuration of building-integrated renewable energy systems (solar-thermal collectors and photovoltaic panels) can be effectively supported via reliable computation of incident solar radiation. Toward this end, advanced building energy and lighting simulation programs adopt high-resolution sky models. The present contribution addresses the reliability of two such models based on long-term high-resolution data collected at the observatory of the Department of Building Physics and Building Ecology at TU Vienna, Austria. To evaluate the performance of the sky models, we compared simulated and measured vertical illuminance values as well as patch luminance values. The statistical appraisal of the comparison points to limits in the predictive accuracy of both models.

INTRODUCTION

Deployment of performance simulation in building design and control phase can enhance the buildings' performance in their life cycle. This requires reliable input data for simulation models. Specifically, obtaining high-resolution solar radiation data can represent a challenge. Several authors have proposed models to predict the distribution of radiance and luminance over the sky hemisphere based on global and diffuse horizontal irradiance and illuminance data (CIE 1955, CIE 1973, Nakamura *et al.* 1985, Matsuura and Iwata 1990, Perez *et al.* 1993, Brunger and Hooper 1993, CIE 1994, Igawa *et al.* 1997, Kittler *et al.* 1997, Kittler *et al.* 1998, Tregenza 1999, CIE 2003, Mahdavi and Dervishi 2013). Among these models, CIE (CIE 1955, 1973) and Perez (Perez *et al.* 1993) are widely used and are embedded in the RADIANCE simulation application (Ward 1994). This paper reports on the comparison of predicted vertical illuminance values (obtained using the above mentioned sky models) with corresponding measurements for the location Vienna, Austria. Moreover, predicted and measured sky luminance values were compared for 145 distinct sky patches representing the sky dome.

APPROACH

Data

Department of Building Physics and Building Ecology at TU Wien is equipped with an advanced microclimatic monitoring station. This station is located at the rooftop of the main building of the university, which is situated in the Vienna city centre. It houses radiometric and photometric sensors that measure global and diffuses horizontal irradiance and illuminance, global vertical irradiance and illuminance for four cardinal orientations, as well as sky radiance and luminance values for discrete sky patches. To assess the performance of the models in capturing the sky luminance distribution, we used the measured illuminance data incident on the aforementioned four vertical surfaces. We also collected patch luminance data using a sky scanner (EKO instruments 2014). The measured horizontal global (or direct normal) and diffuse irradiance data was used as input for Perez *et al.* and CIE models to generate the sky luminance distributions. In the present contribution, we use 15-minutes interval data collected in the period between April to the end of the year 2014.

Models

Combining physical principles and a large set of experimental data, Perez (Perez *et al.* 1993) introduced a model to predict the relative sky luminance for discrete sky patches (L_r). The model contains two variables and five coefficients (Eq. 1). The variables are the zenith angle of the considered sky point and the angular distance between the sky point and the sun disk. The coefficients resulted from least square fitting of the data and can be obtained from a table.

$$L_r = \left[1 + ae^{\frac{b}{\cos(Z)}}\right]\left[1 + ce^{d\xi} + e\cos^2(\xi)\right] \qquad (1)$$

Here, L_r is the relative luminance, which is the ratio of sky luminance over zenith luminance (L_z), ξ is the angular distance between the sky element and the sun disk, Z is the zenith angle of considered sky element and a, b, c, d, and e are the mentioned coefficients. In order to select the values of the five coefficients from the table, two variables, namely, sky brightness (Δ) and sky clearness (ϵ) must be calculated (Eq. 2, 3).

$$\epsilon = \frac{\left[\frac{I_{h.dif} + I_{n.dir}}{I_{h.dif}} + 1.041 Z_s^{\ 3}\right]}{1 + 1.041 Z_s^{\ 3}} \tag{2}$$

$$\Delta = \frac{m_{air} I_{h.dif}}{I_{n.ext}} \tag{3}$$

Here, $I_{h.diff}$ is the horizontal diffuse irradiance, $I_{n.dir}$ the normal direct irradiance, Z_s the solar zenith angle, m_{air} the optical air mass, and $I_{n.ext}$ the extraterrestrial normal irradiance. $I_{n.dir}$ is generated based on a diffuse fraction model (Perez *et al.* 1991). Zenith luminance (L_z) was calculated according to Perez *et al.* 1990.

International Commission on Illumination (CIE 2003) distinguishes 15 sky types. For each sky type, CIE offers a specific formula to calculate the Luminance values. To deploy this version of the CIE model, for each instance, we calculated 15 types of sky luminance and chose the best fitting sky type based on RMSE with sky scanner data. The ratio of the patch luminance L_i to zenith luminance L_z is expressed as follows:

$$\frac{L_i}{L_z} = \frac{f(\mathcal{X})\phi(Z)}{f(Z_s)\phi(0°)} \tag{4}$$

X is calculated using the following equation:

$$\mathcal{X} = arc\cos^{-1}(\cos(Z_s)\cos(Z) + \sin(Z_s)\sin(Z)\cos(A_z)) \tag{5}$$

Here, A_z is azimuth angle difference between sun disk and patch element. In this case, zenith luminance (L_z) was derived based on Darula and Kittler (2002).

None of the models estimates the sun disk luminance. In fact, they calculate the diffuse luminance distribution. In order to estimate the sun disk luminance value for each instance, direct normal illuminance measured data was converted to sun disk luminance:

$$L_{sun} = \frac{E_n}{\pi(\sin^2(^{\eta}/_2))} \tag{6}$$

Here, L_{sun} is sun disk luminance, E_n is direct normal illuminance, and η is sun disk angle (assumed 0.533°).

After adding the sun disk luminance, all patch values were normalized to the horizontal global illuminance:

$$L_i^{norm} = \frac{E_{h.g}}{\sum_{i=1}^{145}[\Omega_i \cos(Z_i)]} L_i \tag{7}$$

Here, L_i^{norm} is the normalized patch luminance and $E_{h.g}$ is the horizontal global illuminance.

Note that it is not possible to differentiate between the 15 CIE skies solely on the basis of weather station data. Therefore, for each instance we selected the sky category that yielded the closest results to the measured patch luminance data.

Comparison

We implemented both models in MATLAB (2010). For comparison purposes, vertical illuminance values were derived from patch luminance values of two sky models:

$$\psi_i = \Omega_i \cos(\varphi_i)\cos(\varphi_i - \beta) \tag{8}$$

$$E_{ver,\beta} = \sum_{i=1}^{145} L_i \psi_i \tag{9}$$

Here, ψ_i is i^{th} patch vertical transformation function, Ω_i is i^{th} patch solid angle, φ_i is the i^{th} patch azimuth angle, β is the vertical plane normal angle, L_i is i^{th} patch luminance values, and $E_{ver,\beta}$ is vertical illuminance value in the direction of β.

Model-based predictions of vertical illuminance values were compared with corresponding measured vertical illuminance for the aforementioned 8 months period. Moreover, to evaluate the accuracy of the sky luminance distribution predicted by the two models, we also utilised the sky scanner luminance measurements for 145 discrete sky patches. Thus, a patch-to-patch comparison of calculated and measured luminance values could be facilitated for data obtained for the same period. The evaluation statistics deployed included root mean square error (*RMSE*), coefficient of determination (R^2), relative error (*RE*), coefficient of variation of *RMSE* (CV_{RMSE}), and mean bias error (*MBE*).

RESULTS

Table 1 provides an overview of the main results. Thereby, measured and predicted vertical illuminance and patch luminance values were compared. Note that RMSE and MBE values for vertical illuminance values are given in units of klx, whereas those for patch luminance values are given in kcd.m^{-2}.

Table 1
Statistical evaluation of CIE and Perez et al. models based on vertical illuminance predictions

ORIEN.	MODEL	R^2	RMSE	CV_{RMSE}	MBE
North	CIE	0.90	2.05	18.41	-0.05
	Perez	0.87	2.34	21.00	-0.13
East	CIE	0.97	6.29	23.66	-1.56
	Perez	0.97	6.55	24.64	-0.60
South	CIE	0.95	8.77	25.52	-3.56
	Perez	0.94	8.94	26.00	-1.76
West	CIE	0.96	7.20	26.40	-1.11
	Perez	0.95	7.64	28.03	0.08
Patch	CIE	0.88	3.54	43.13	-0.05
	Perez	0.82	4.32	52.65	0.32

The distributions of the relative errors of the illuminance predictions for the four surface orientations are depicted in Figure 1. Figure 2 shows, for both sky models, the cumulative distribution function of percentage of results with relative errors (%) of calculated vertical illuminance values. Likewise, Figure 3 illustrates relative errors in calculation of patch luminance values in terms of cumulative distribution functions

To gain a general impression of the models' performance, consider the percentages of results with relative errors less than 20% (see Table 2, Figure 2). Note that the CIE model's slightly better performance must be viewed in the context of the aforementioned use of measured patch luminance data toward the instance-by-instance selection of the sky category.

Table 2 The percentages of results with relative errors less than 20%

	North	East	South	West	Patch
CIE	82	80	74	75	51
Perez	72	77	71	70	46

CONCLUSION

Illuminance on four vertical surfaces as well as luminance values of 145 sky patches were estimated using two sky models (Perez *et al.*, CIE). The comparison of the computational results with corresponding high-resolution measurements conducted in Vienna point to a rather limited predictive potency. Hence, these sky models would have to be substantially improved – or at least calibrated – to reproduce the measured data with sufficient accuracy. Future research will pursue a collaborative multi-location model comparison using larger data sets and more detailed statistical analyses.

ACKNOWLEDGEMENTS

The research presented in this paper was supported in part within the framework of the "Innovative Projekte" research funding program of the Vienna University of Technology. Mr. Josef Lechleitner supported the authors with regard to the retrieval and pre-processing of the microclimatic monitoring station data.

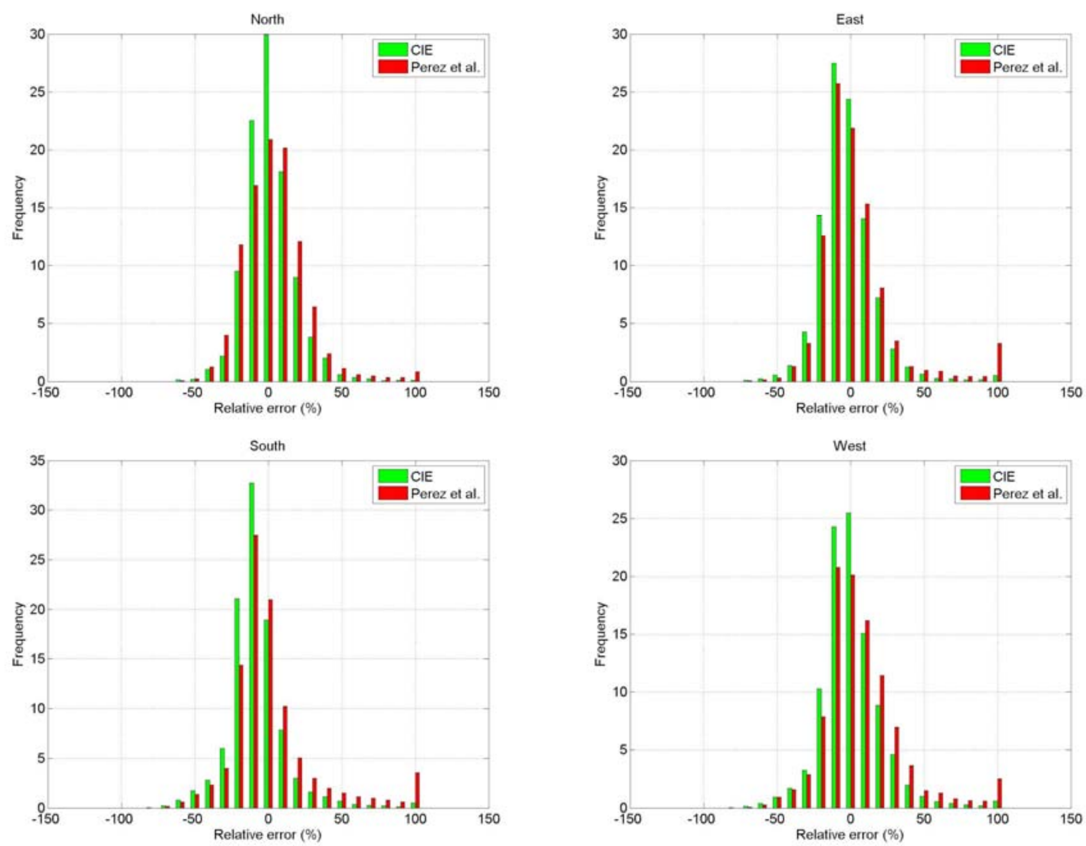

Figure 1 Comparison of the CIE and Perez sky models in terms of relative error distributions of predicted vertical illuminance values (Note that the Relative Errors over 100% are merged into the 100% error bin)

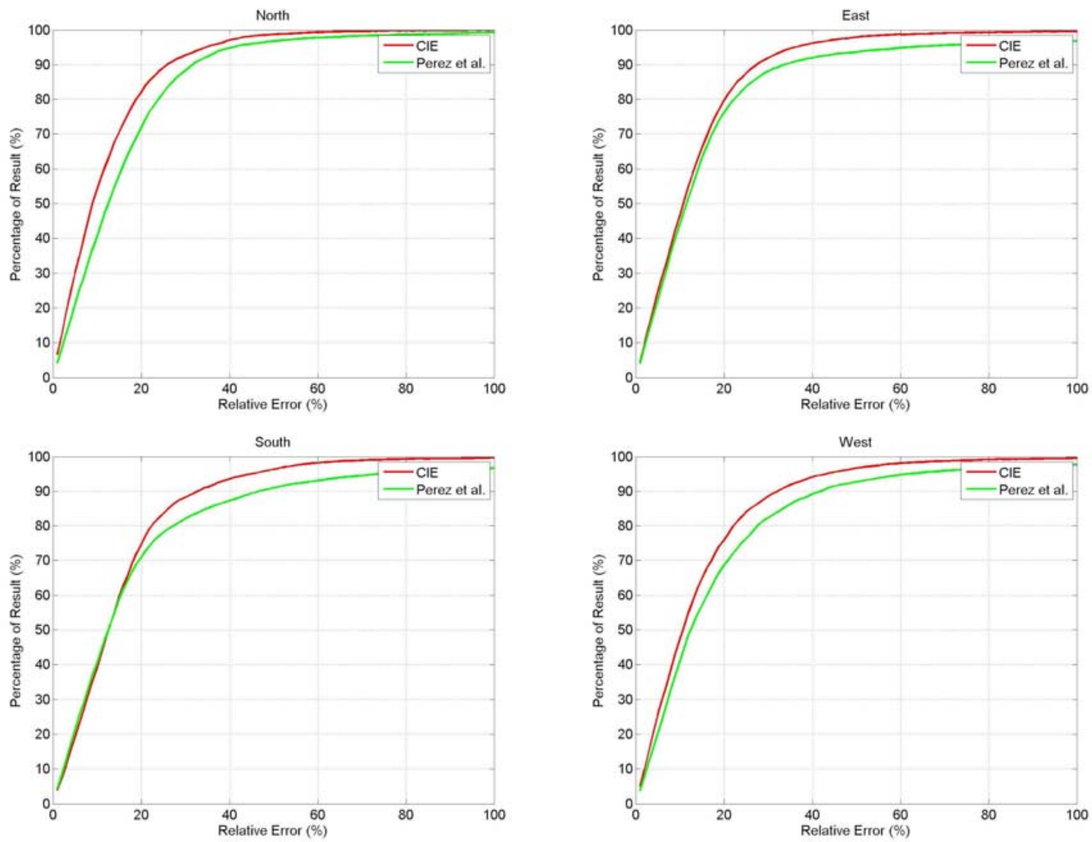

Figure 2 Comparison of CIE and Perez et al. sky models' relative errors (%) for vertical surfaces facing the four cardinal directions in terms of cumulative distribution functions

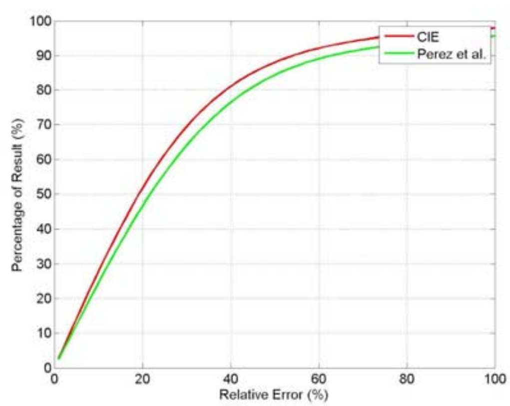

Figure 3 Cumulative distribution functions of the relative errors (%) of the two models' patch luminance predictions

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