# A SIMPLE METHOD FOR THE DERIVATION OF ILLUMINANCE VALUES FROM RADIANCE DATA

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## ABSTRACT

Daylight simulation applications require information on sky luminance distribution. Sky distribution maps can be generated synthetically, but the process requires external illuminance information for calibration purposes. As measured external illuminance levels are not available for many locations, the more widely available irradiance measurements can be translated, using proper luminance efficacy functions, into illuminance values. In this context, the present paper compares five alternative luminous efficacy models for the prediction of external illuminance based on irradiance. The first option is based on a fixed global luminous efficacy assumptions. The other options consider potential dependencies of luminous efficacy on outdoor temperature and humidity ratio. The models are first derived based on a first set of measured data and then test against a second set of empirical observations.

Keywords: luminous efficacy, irradiance, illuminance, temperature, humidity ratio

## 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 illuminance data.

In previous research (Mahdavi et al. 2006), we illustrated the use of calibrated digital photography toward determination of the luminance distribution of the sky dome. Thereby, we demonstrated how a low-cost digital camera with a fish-eye lense couples with a illumionance meter can provide such detailed luminance distribution data reliably. As comprehensive measured external illuminance data is not available for most locations, approaches are needed to estimate external illuminance based on more widely available global irradiance data. A well-known approach for this purpose involves the use of luminous efficacy, which denotes the relationship between illuminance and irradiance in lumens per Watt.

In the past decades, several authors have studied the luminous efficacy of the solar radiation using algorithms for the different sky conditions. Littlefair (1988) suggested differrent luminous efficacy values for different sky conditions (overcast sky, clear sky, intermediate sky). Perez et al. (1990) developed luminous efficacy models as a function of the sun position, the brightness of the sky, and the sky's clearness variables. The parameteres were devided in intervals and the changes of luminous efficacy were studied. Wright et al. (1989) besides the three parameters used a fourth parameter in the study of luminous efficacy: the total percepitable water W, calculated as a function of dew point temperature (°C). Chung (1992) and Robledo et al. (2000) develop local luminous efficacy models for overcast and intermediate skies based on Littlerfair's model. Muneer and Kinghorn (1997) developed global and diffuse luminous efficacy models as a regression function of clearness index *k*.

The present work evaluates five options regarding luminous efficacy models using data obtained for Vienna, Austria. This evaluation, besides the fixed luminous efficacy assumption, also presents polynomial models obtained when plotting the global luminous efficacy against the temperature and humidity ratio for different global horizontal irradiance ranges.

## APPROACH

To obtain the input data needed to derive luminous efficacy values (η), we established a first set of measured global horizontal illuminance and irradiance data, as well as external temperature and relative humidity over a period of three years using the microclimatic monitoring station of the Department of Building Physics and Building Ecology at the Vienna University of Technology, Vienna, Austria. The measurements were organized in terms of a data base containing information collected every fifteen minutes during the three-year observation period (from 1rst of January 2005 to 31 of December 2007), resulting in measured values for 34.992 discrete intervals. Only intervals with daylight were taken into account. The measurement period included a variety of sky conditions, from sunny, to partly cloudy, to overcast.

We tested five options to derive illuminance levels from irradiance levels using luminous efficacy values. The first option (A) involves the use of a fixed luminous efficacy value. The second option (B) assumes that luminous efficacy value depends on the outdoor air temperature. Thereby, a linear relationship between lumious efficacy and outdoor air temperature (θ) is established for the entire range of external global horizontal irradiance (from 50 to 1100 $W.m^{-2}$). The third option (C) assumes that luminous efficacy value depends on the humidity ratio (HR) of the outdoor air. Again, a linear relationship between lumious efficacy and humidity ratio is established for the entire range of external global horizontal irradiance. The fourth option (D) is similar to the second option (B), other than in this case, three ranges of horizontal irradiance data are considered. The fifth option (E) is similar to the third option (C), other than also in this case, three ranges of measured irradiance data are considered. These options are shown in table 1. The above mentioned three irradiance ranges are given in table 2.

*Table 1. Overview of the five options*

| Option | Method of derivation of luminous efficacy (η) |
|---|---|
| A | One η value based to the mean of all data |
| B | η corrected as a linear function of the temperature (for the entire irradiance range) |
| C | η corrected as a linear function of the humidity ratio (HR) (for the entire irradiance range) |
| D | η corrected as a function of the temperature for 3 ranges |
| E | η corrected as a function of the humidity ratio for 3 ranges |

To compare these options, the respective luminous efficacy functions (derived based on the above mentioned 3-year data set) were used to derive external global horizontal illuminance values based a second set of measured irradiance data (collected using the same monitoring station for the period of January first 2008 to 31. of July 2009). The derived illuminance data were then compared with corresponding measurements for this second montioring period.

To compare the options statistically, Relative Error (RE) was used. For a pair of values (such as derived and measured illuminance levels), RE can be expressed as per equation 1.

$$RE_i = \frac{M_i - C_i}{M_i} . 100 \quad [\%] \qquad (1)$$

In this equation, $M_i$ and $C_i$ denote the measured and derived illuminance at interval i respectively.

## RESULTS AND DISCUSSION

Figures 1 and 2 show empirically derived luminous efficacy values (for all intervals of the first data set) as a function of outdoor air temperature and outdoor humidty ratio respectively. The associated regression functions provided the basis of the aformentioned options B and C (see Table 1). Figures 3 to 5 show empirically derived luminous efficacy values (for all intervals of the first data set) as a function of outdoor air temperature for three different irradiance ranges. The associated regression functions provided the basis of the aformentioned option D (see Table 1). Figures 6 to 8 show empirically derived luminous efficacy values (for all intervals of the first data set) as a function of outdoor humidity ratio for three different irradiance ranges. The associated regression functions provided the basis of the aformentioned option E (Table 1). An overview of these regression functions is provided in Table 2.

To compare the performance of the five options (Table 1), Figure 9 shows the percentage of the results (pairs of measured and derived illuminance levels) with associated maximum relative errors for the five above-mentioned options. Note that, for this comparison only data from the second measurement period was used. Moreover, data captures in Figure 9 was used to generate the numerical data in Table 3. Thereby, for descrete values of relative error (±5%, ±10%, ±15%, ±20%), the associated percentage of results are given.

Figures 1 to 8 suggest higher correlation coefficient values for higher irradiance ranges.

Figure 9 implies that options C and E (which work with humidity ration) display slightly lower relative errors than the other options. Likewise, Table 3 suggest that option E performs generally better than the other options.

Overall, the differences between the options in view of relative error are not highly pronounced. However, option A (which uses a fixed value for luminous efficacy) does display the highest relative error.

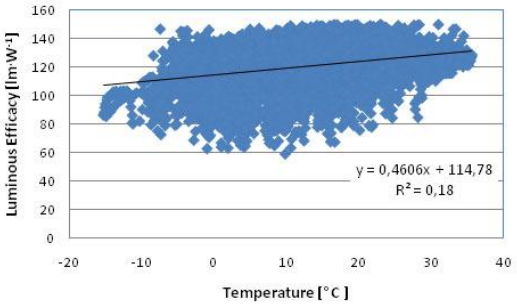


*Figure 1 Luminous efficacy as a function of outdoor air temperature (irradiance range: 50 to 1100 W/m²)*

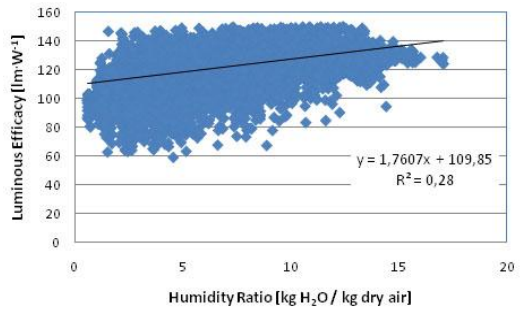


*Figure 2 Luminous efficacy as a function of humidity ratio (irradiance range: 50 to 1100 W/m²)*

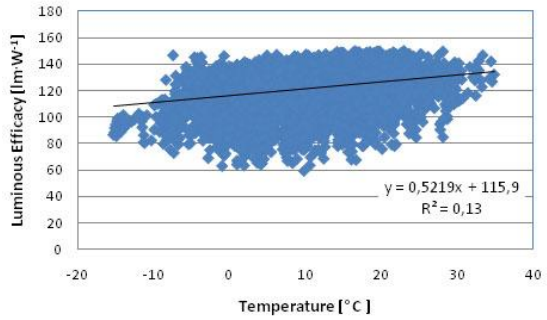


*Figure 3. Luminous efficacy as a function of outdoor air temperature (irradiance range: 50 to 300 W/m²)*

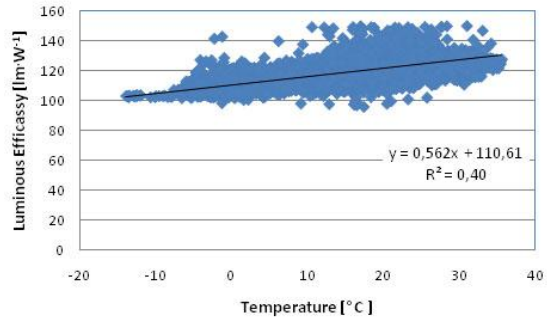


*Figure 4 . Luminous efficacy as a function of outdoor air temperature (irradiance range: 300 to 600 W/m²)*

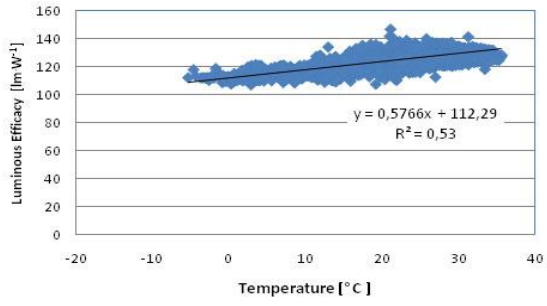


*Figure 5 Luminous efficacy as a function of outdoor temperature (irradiance range: 600 to 1100 W/m²)*

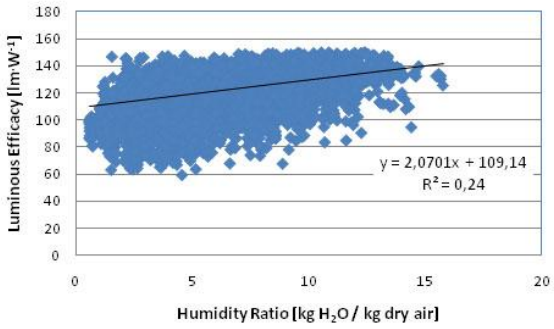


*Figure 6 Luminous efficacy as a function of humidity ratio (irradiance range 50 to 300 W/m²)*

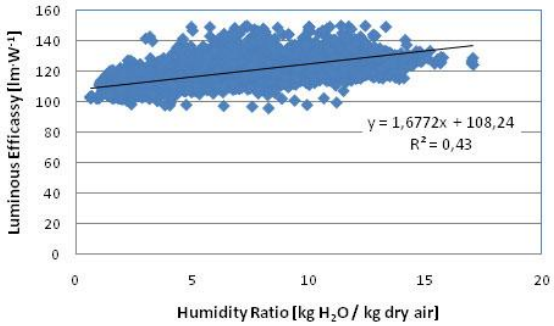


*Figure 7 Luminous efficacy as a function of humidity ratio (irradiance range: 300 to 600 W/m²)*

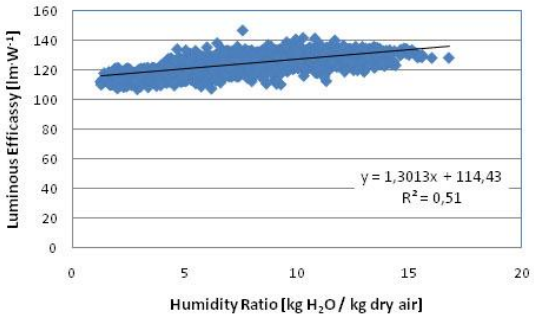


*Figure 8 Luminous efficacy as a function of humidity ratio (irradiance range: 600 to 1100 W/m²)*

*Table 2 Overview of the regression functions expressing the dependency of luminous efficacy on outdoor air temperature and humidity ration for different ranges of global horizontal irradiance*

| | | | |
|---|---|---|---|
| Radiance range [W.m$^{-2}$] | 50 to 300 | $\eta = 0{,}5219\ \theta + 115{,}9$ | $\eta = 2{,}0701\ HR + 109{,}14$ |
| | 300 to 600 | $\eta = 0{,}562\ \theta + 110{,}61$ | $\eta = 1{,}6772\ HR + 108{,}24$ |
| | 600 to 1100 | $\eta = 0{,}5766\ \theta + 112{,}29$ | $\eta = 1{,}3013\ HR + 114{,}43$ |
| | 50 to 1100 | $\eta = 0{,}4275\ \theta + 115{,}48$ | $\eta = 1{,}7607\ HR + 109{,}85$ |

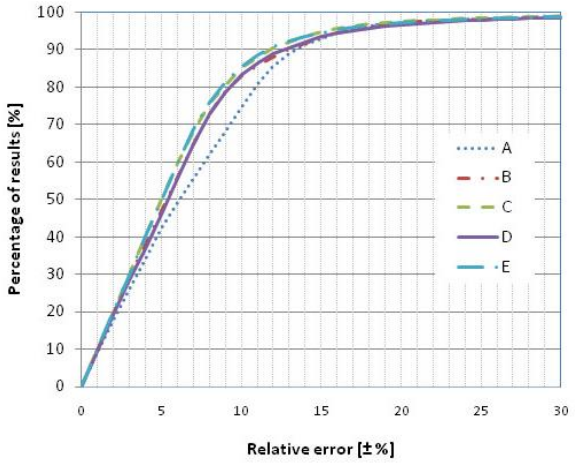


*Figure 9 Percentage of the results (pairs of measured and derived illuminance values) with respective maximum Relative Error for the five options*

*Table 3 Percentage of results with different maximum Relative errors*

| Option | ± 5 % | ± 10 % | ± 15 % | ± 20 % |
|---|---|---|---|---|
| A | 42.3 | 74.8 | 93.1 | 97.3 |
| B | 47.1 | 83.2 | 93.2 | 97.0 |
| C | 50.2 | 85.1 | 94.6 | 97.6 |
| D | 46.1 | 83.2 | 93.4 | 96.6 |
| E | 49.8 | 85.5 | 94.8 | 97.9 |

## CONCLUSION

We compared a number of different options to derive illuminance values from the more widely available measured global horizontal irradiance data using alternative luminous efficacy functions. These functions can be incorporated in simulation applications for the daylight analysis and design support. The results suggest that two options (C and E), which use humidity ratio information to formulate luminous efficacy functions delivered somewhat better results. However, the range of errors was rather low for all options. Even for the worst-ranked option (A), the relative errors were in 75% of the cases less than ±10%.

Additional experimental studies need to be carried out to further explore the statistical validity and significance of the results. In addition, the above-mentioned luminous efficacy models need to be further evaluated against existing luminous efficacy models such as those suggested by Littlefair (1998), Perez et al. (1990), Chung (1992), and Muneer and Kinghorn (1997). Moreover, the applicability of the derived functions to other local and regional circumstances must be further explored. Likewise, a comparision of the derived functions with alternative methods proposed in past research efforts must be carried out.

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