A model to estimate diffused luminous efficacy based on satellite data

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Abstract

A constant value and universal models of luminous efficacy for diffused solar radiation on a horizontal surface were developed and presented in this study. They are based on satellite derived data available via web servers, and applicable to all sky conditions. Solar radiation data from ten locations in Europe and North Africa was used to obtain two functions for luminous efficacy (K) against solar altitude (α), and sky clearness index (k_t). All were used to estimate illuminance for the ten originating locations; for four locations based on satellite data; and for a further five based on measured data. A statistical assessment showed that the best models are constant value of 123lm/W and K against α. Comparison between results from the proposed models and those produced using three published models, indicate that the former produce more accurate estimates of luminous efficacy. The satellite based approach makes daylight data available in locations remote from current measurement sites.

Keywords

Daylight, luminous efficacy, diffused, illuminance, irradiance, satellite.

1. Introduction

Innovative daylighting systems developed over the last few years attempt to deliver daylight into areas remote from the building envelope. There is a general dearth of measured illuminance data for combinations of sunlight and skylight which are necessary to permit the estimation of daylight delivery from these systems in worldwide locations. As a result, luminous efficacy models can be used to relate direct, global and diffuse radiation components to their photopic equivalents. They enable the calculation of daylight illuminance from the more widely available irradiance data. Luminous efficacy is defined as the ratio between illuminance and irradiance. Thus, if E is the illuminance in lux and I is the irradiance in W/m^2, the luminous efficacy of the solar radiation, K, will be given by:

$$K=E/I \quad \text{(lm/W)} \qquad (1)$$

Work by the authors [1] developed universal models to estimate direct luminous efficacy based on free-access satellite data. This work suggests models to estimate diffused luminous efficacy using a similar procedure.

2. Review of diffused luminous efficacy models

Luminous efficacy published models were classified into three groups according to the variables used. The first uses solar altitude as the only independent variable [2-7]. The second group uses metrological parameters as independent variables [3, 6, 8-11]. The last group uses constant values without any variables [12].

Most models in the first group are based on polynomial expressions of different degrees functions of solar altitude, and specific to sky type. Meanwhile, the models in the second group were developed from either meteorological parameters or experimental data from specific locations, but are intended to represent all sky types. The third group suggests constant values for luminous efficacy for each of global, diffuse and direct irradiance.

3. The proposed model of diffused luminous efficacy

3.1. Aims and advantages

The current work seeks to develop validated universal models for the diffused horizontal luminous efficacy valid for all skies using satellite-based website data. The independent variables used are available for all points on the earth's surface in free-access web servers. It is not necessary to determine local sky conditions to use the current model and no local coefficients are included.

3.2. Data sources

Data obtained from two sites were used to develop the present models. The European database of daylight and solar radiation website, Satel-light [13], is used in this work to provide diffused irradiance and illuminance data, from which luminous efficacy for the selected locations is directly calculated. Data is available for any defined surface orientation for the period 1996 to 2000. The second source is NASA Surface meteorology and Solar Energy (SSE) [14], which used to obtain data of independent variables such as hourly solar altitudes.

3.3. Choice of locations

The calculations are based on data for locations which are broadly representative of conditions throughout the area covered by Satel-light. The ten locations include both maritime and continental cities; and latitudes from 55°N to 35°N at intervals of about 5°. Table 1 lists the selected cities and their locations and altitudes, and the frequencies of occurrence of the characteristic sky conditions of the locations.

Table 1 Locations frequencies of sky conditions and Luminous Efficacy.

		Location Conditions			Sky Conditions (%)			K_d (lm/W)		
CITY	Country	Lat.	Lon.	Alt.	Sun	Intermed.	Overcast	Max.	Min.	Mean
Copenhage	DK	56	13	0	34	38	28	150	100	120.2
Moscow	RU	56	38	155	35	40	25	127	100	121.2
London	UK	51	0	15	31	42	27	130	116	122.1
Kiev	UA	50	31	169	38	35	27	130	118	123.9
Bordeaux	FR	45	1	9	47	34	19	135	117	127.1
Bucharest	RO	44	26	84	49	31	20	128	100	120.5
Valencia	ES	39	0	11	70	20	10	129	100	121.8
Athena	GR	38	24	110	68	21	11	130	119	124.0
Nador	MA	35	03W	155	67	24	9	126	118	121.9
Khania	GR	36	24	1	69	19	12	139	121	127.0

3.4. Statistical indicators

Statistical indicators used include mean bias deviations (MBD), and root mean square deviations (RMS). They are defined by the following equations:

$$MBD= \sum_{i=1}^{N}[(y_i - x_i)/x_i \,.\, 100]/N \qquad (2)$$

$$RMS= [\sum_{i=1}^{N}[(y_i - x_i)/x_i \,.\, 100]^2/N]^{1/2} \qquad (3)$$

Where: y_i is the estimated value, x_i is the given value (selected from Satel-light in the present work) and N is the number of values.

4. Development of the proposed diffused model

Diffused horizontal illuminance and irradiance data was obtained from Satel-light for ten 'originating' locations. From each the diffused horizontal 'reference luminous efficacy' K_d, was calculated using Equation 1. Table 1 lists the maximum, minimum and mean reference values for each location. There are some differences between minimum and maximum values, but mean values are close to some extent. The average of the maximum, minimum and mean reference values are 132lm/W, 111lm/W and 123lm/W respectively.

Using solar altitude, α, as the only independent variable, linear function for K_d against α was obtained by plotting the variation of K_d with α for all ten originating locations. Figure 1 shows the best fit curve, which is as follows:

$$K_{d1} = 0.0215\,\alpha + 122.52 \qquad (4)$$

Using clearness index, k_t, as a sole independent variable, the variation of K_d plotted against the k_t for all ten originating locations. Figure 2 shows the best fit polynomial curve, which is as follows:

$$K_{d2} = 29.492\, k_t^{\,3} - 13.805\, k_t^{\,2} + 3.5567\, k_t + 121.83 \qquad (5)$$

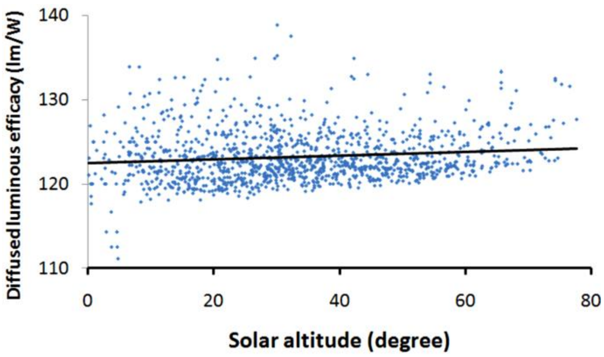

Fig1. D. luminous efficacy against solar altitude

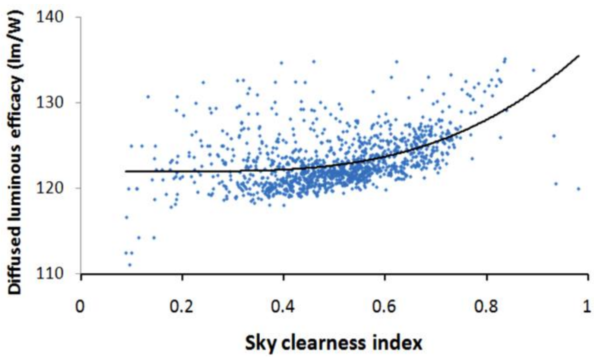

Fig2. D. luminous efficacy against clearness index

5. Statistical performance of the proposed models

The proposed models have been used to generate diffused illuminance values for the ten 'originating locations'. The generated values were compared with the actual values for the corresponding locations. In addition four more locations were added as 'validation locations'. These were:

Oslo, NO	(60˚N, 11˚E)	Berlin, DE	(52˚N, 13˚E)
Parma, IT	(45˚N, 10˚E)	Alger, DZ	(37˚N, 3˚E)

Figure 3 shows the statistical performance of the models described by Eqs. (5 & 6); named M-1 and M-2 respectively. The statistical performance of the developed models proved a big agreement between the originating and validation locations. The results show slight superiority of M-2 against M-1 in terms of RMS, and very similar results in terms of MBD; for either originating or validation locations. M-2 has the following statistical performance averages: RMS = 2.2% and MBD = 0%, which obtained from the originating locations. And the following averages from the validation locations: RMS = 1.9% and MBD = 0.3%. Originating and validation location performances showed a very satisfying agreement. M-2 performance is more stable than the other model in terms of MBD, but very similar to it in terms of RMS. That is noted from the variations of the statistical indicators over the fourteen locations. The differences between minimum and maximum values of RMS and MBD for M-2 are 2% and 3.5% respectively, in compare with 2.6% and 5% for M-1. It is worth mentioning that underestimation of luminous efficacy tends to occur in the Southern locations.

Comparison between the averages of reference and estimated efficacies values shows the following: the differences between the maximum values are 8 and 4 lm/W for M-1 and M-2 respectively, and between the minimum values are -12 and -11lm/W at the same sequence. Negligible difference of -0.2lm/W is noted between the average mean values for both models. The differences between the models in terms of maximum and minimum values are significant whilst in terms of mean values is negligible.

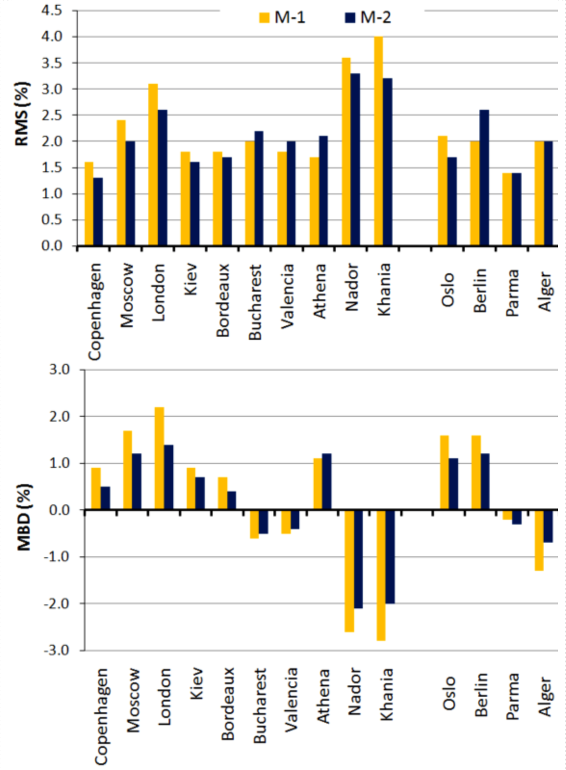

Fig 3. Statistical assessment of diffused developed models

The statistical performance tends to favour M-2 model, but the simplicity of M-1 may make it more favourable particularly the difference is very slight and the latter satisfies the purpose of simplicity aimed in this study. The differences between the 'estimated efficacies values' doesn't give any preference for any of the models.

6. Published models

All models mentioned in the review were evaluated using satellite data, and those that gave the best results used for comparison with the proposed models. The models considered for estimation of the diffused luminous efficacy on horizontal surface were:

- Muneer's model [10], which expresses the correlated K_d solely to the k_t as a second degree polynomial of k_t. The following formula based on a measured data from five sites in the UK:

$$K_{d3} = 130.2 - 39.828\, k_t + 49.9797\, k_t^{\,2} \quad (6)$$

- Robledo's model [6], which correlated the K_d to the sinus of solar altitude and to sky brightness index Δ. The following formula for all skies based on a measured data from Madrid.

$$K_{d4} = 82.24(\sin \alpha)^{-0.034}\, \Delta^{-0.266} \quad (7)$$

- Ruiz's model [11], which correlated the K_d to the sinus of solar altitude and to diffused clearness index k_d. The following formula based on a measured data from Madrid.

$$K_{d5} = 86.97(\sin \alpha)^{-0.143}\, k_d^{-0.218} \quad (8)$$

7. Statistical performance of the published models

The published models have been used to generate illuminance values for all the originating and validation locations. Thus the generated values were compared with the actual values for the corresponding locations.

Quick comparison between Ruiz's model and the other two rapidly dismiss it. Its RMS and MBD respectively are no less than 14.2% and 10.1%, which is far behind the other two models statistical performance. The average statistical performance of Muneer's models is 3.3% and 0.7% for RMS and MBD respectively; in compare with 7.6% and 4.9% for Robledo's (see table 2). Both of them showed a similar stability around 2.2% in terms of RMS, whilst in terms of MBD Robledo's leads with stability of 1.9% against 3.6% for Muneer's. Since Muneer's model performs more than two times better than Robledo's, the stability has nothing to do with its superiority.

Comparison between the averages of each of the reference and estimated efficacies values shows the following: the differences between the maximum values are 2 and -24 lm/W for Muneer's and Robledo's respectively, between the minimum values are-11 and 0 lm/W, and between the mean values are -0.7 and -5.9 lm/W (see table 2).

The statistical performances and estimated efficacies of the published models suggest that Muneer's model is the best in estimating illuminance data from satellite irradiance data.

8. Comparison of models

Statistical performances and differences between reference and estimated luminous efficacies over the fourteen locations were used to compare between developed and published models, in addition to constant luminous efficacy value of 123lm/W, which represents the average of the mean diffused efficacies values for all the originating locations. The derived constant value is equal to that suggested by De Rosa**[12]**.

From table 2 it can be noticed that among the developed models; M-2 shows the best statistical performance with very slight margin. The best performing published models as it is clear in table 2 is Muneer's model. The constant value gave the same average performance as the developed models. Taking the statistical performance into account, Muneer's RMS is 1% more than the constant value and the developed models, and its MBD is only 0.5% more. Figure 4 illustrates the similarity of the constant

Table 2 Statistical performance of all models

Models		RMS (%)	MBD (%)	K_d differences Max	Min	Mean
M-1	[Eq. 4]	**2.2**	**0.2**	8	-12	**-0.2**
M-2	[Eq. 5]	**2.1**	**0.1**	4	-11	**-0.2**
Constant	123	2.3	**0.2**	-	-	-
Muneer	[Eq. 6]	3.3	0.7	**2**	-11	-0.7
Robledo	[Eq. 7]	7.6	4.9	24	**0**	-5.9

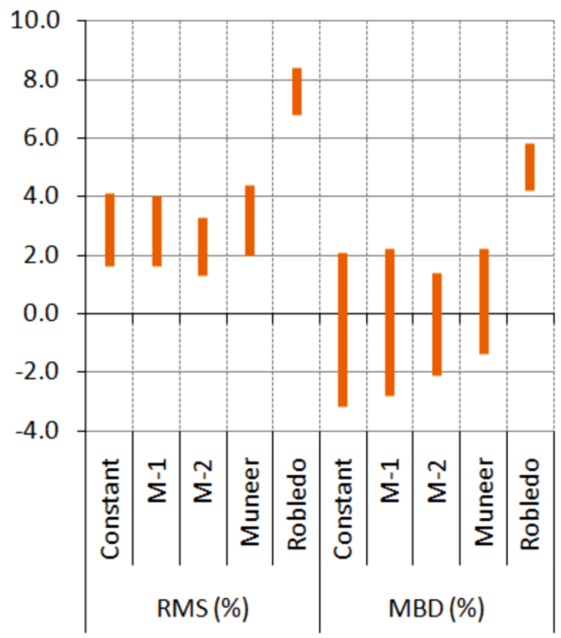

Fig 4. Statistical indicators ranges of the constant value and diffused developed and published models

value, M-1, M-2 and Muneer's model, and the difference between them and Robledo's model. The RMS indicator shows values of around 2.3% for the constant value and developed models, whilst 3.4% and 7.6% are the ranges of Muneer's and Robledo's models respectively; with best stability of 2% for M-2. The MBD indicator tells that Robledo's model is the most stable one with difference of 1.6% though gained the highest range around 4.9%; in compare with 0% for the constant value and developed models, and 0.7% for Muneer's.

Estimated efficacies values by the developed models gave means of negligible differences with the reference mean. Muneer's model gave very reasonable mean with only 0.7% difference, while Robledo's difference of 5.9% is unreasonable.

9. Application of the proposed and published models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data from the following locations:

Edinburgh, UK	(55.93˚N, 3.30˚W)	Bratislava, SK	(48.17˚N, 17.08˚E)
Arcavacata, IT	(39.36˚N, 16.22˚E)	Fukuoka, JP	(33.52˚N, 130.48˚E)
Hong Kong, CN	(22.40˚N, 114.11˚E)		

The statistical performances of the developed models, and the published Muneer's and Robledo's models, in addition to the constant value 123lm/W, are as presented in table 3, which shows that Robledo's model best performs in Fukuoka only and keep in distance in all other locations. The performances of all the others are generally close that the difference between any two indicators doesn't exceed 1.3% except in two cases; reached 2.3% and 2.5%. Yet there are slight differences justify the following ranking: M-2 is the best performing in Edinburgh, combined with the constant value in Hong Kong, additionally combined with M-1 in Bratislava, and all joined with Muneer's model in Arcavacata. In terms of average performance over all locations, the RMS for all of them is 14.3-14.6%, but Robledo's is 25.1%.

Robledo's model has shown lake as well in the stability indicator with values of 33% and 40% for RMS and MBD respectively. The others have showed close stabilities to some extent. The range of RMS is 13.7-15% with superiority for M-1 and the constant value. MBD stability range is 23.8-24.2% with superiority for M-2 and the constant value.

The previous comparison shows that constant value of 123lm/W gives the best performance along with the developed model M-1; the linear formula of solar altitude, and M-2; the third degree polynomial formula of clearness index, in addition to Muneer's model; the second degree polynomial formula of clearness index. Since they give very close results, their rank due to their simplicity is the constant value first, then the linear formula of solar altitude M-1.

Table 3 Average statistical performance of proposed and published models

	Edinburgh		**Bratislava**		**Arcavacata**		**Fukuoka**		**Hong Kong**	
Models	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)
M-1	6.2	**0.7**	**13.0**	**3.3**	**20.0**	-1.9	19.4	-17.5	14.0	6.6
M-2	**5.3**	**0.8**	**13.2**	**3.2**	**20.2**	-1.2	19.2	-17.4	**13.6**	**6.4**
Constant	6.2	**0.6**	**13.0**	**3.1**	**19.9**	-2.1	19.6	-17.7	**13.8**	**6.2**
Muneer	5.7	1.9	14.0	5.7	20.5	**0.2**	18.5	-16.5	14.3	7.7
Robledo	14.3	1.7	47.8	28.1	24.7	8.7	**16.1**	**-12.4**	22.4	11.6

10. Conclusion

New methods have been suggested in this work to estimate horizontal diffused luminous efficacy; based on widely available satellite data on web servers free of charges. The resulting methods are a constant value or a universal model with a minimum requirement for additional variables or coefficients. It makes the availability of realistic design illuminance data independent of the availability of local measured daylight data.

The new approach was developed using satellite irradiance and illuminance data for ten locations in Europe and North Africa. The proposed models were developed from the relation between the luminous efficacy and any of solar altitude or sky clearness index. Among the proposed models, the model based on solar altitude, M-1, emerged as the simplest and best statistically performing model over the fourteen locations throughout Europe and North Africa. In compare with the published models, the statistical performance of M-1 is up to 1.5 times more accurate than the best performing published models, Muneer's model. The constant value achieved similar performance to Md-1 as illustrated in table 2.

In the final part of the work, the constant value, the published and proposed models were used to estimate illuminance data for five locations for which actual diffused irradiance, diffused illuminance and solar altitude data was available. The statistical indicators showed that all of the constant value, M-1 and Muneer's model produce very close estimates of the luminous efficacy. Therefore, simplicity points out the constant value as the most favourable method.

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