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Methods to estimate global and diffused luminous efficacies based on satellite data

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Abstract

This paper presents universal models and constant values to estimate luminous efficacies for each of global and diffused solar radiation on a horizontal surface. They are applicable to all sky conditions and are based on satellite derived data available via web servers. Solar radiation data from ten locations in Europe and North Africa was used to obtain three global and diffused functions for luminous efficacy (K) against solar altitude (α), cloud amount (C), 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 K against α. Comparison between results from the proposed models and those produced using three published models for both cases, indicate that the former produce more accurate estimates of luminous efficacy. Constant values also showed very reliable results, especially for the diffused case. The satellite based approach makes daylight data available in locations remote from current measurement sites.

Keywords: Luminous efficacy; Global illuminance; Diffuse illuminance; Irradiance; Satellite

1. Introduction

There has been resurgence in interest in the use of daylight as an integral part of the lighting systems in energy conscious building design in recent years. Daylight may now be guided or channelled into buildings using a variety of methods. To assess the feasibility of this a detailed knowledge of illuminance conditions at potential locations is necessary (Mayhoub and Carter, 2009). There is a lack of measured illuminance data suitable for this task. As an alternative luminous efficacy models can be used to relate direct, global and diffuse radiation components to their photopic equivalents. These 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

$$K = E/I \quad (\mathrm{lm/W}) \tag{1}$$

Work by the authors (Mayhoub and Carter, 2011) developed universal models to estimate direct luminous efficacy based on free-access satellite data. This work suggests models to estimate global and diffused luminous efficacies using a similar procedure. In addition constant values for both global and diffused luminous efficacies are put forward as a simple substitute for luminous efficacy models where appropriate.

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2. Review of luminous efficacy models

Published models of luminous efficacy can be divided into three groups according to the variables used. The first uses solar altitude as the only independent variable (see Table 1). The second group uses meteorological parameters as independent variables (see Table 2). The last group uses constant values without any variables.

The majority of models listed in Table 1 are specific to sky type and based on polynomial expressions of different degrees functions of solar altitude. They thus could be considered to be one model with different local coefficients. The models set out in Table 2 were developed from either meteorological parameters or experimental data from specific locations, but are intended to represent all sky types. The third group advances constant values for luminous efficacy. De Rosa claims that the latter approach "behaves well and furnishes good results in spite of its simplicity in all skies" (De Rosa et al., 2008). A number of authors among the first two groups have also suggested constant luminous efficacies as a secondary alternative to those produced using functions.

3. The proposed models of luminous efficacy

3.1. Aims and advantages

The current work seeks to develop validated universal models for both global and 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.

Table 1
Global and diffused luminous efficacy models using solar altitude as the only independent variable.

Model	Sky type	Light type
Aydinli and Krochmann (1983)	Clear	Global
Littlefair (1988)	Clear	Direct
		Diffuse
		Global
	Overcast	Global
	Intermediate	Global
Olseth and Skartveit (1989)	Clear	Diffuse
Chung (1992)	Clear	Direct
		Diffuse
		Global
	Overcast	Global
	Intermediate	Global
Ullah (1996)	Clear	Direct
		Diffuse
		Global
	Overcast	Global
	Intermediate	Global
		Diffuse
Robledo and Soler (2000)	Clear	Global
Robledo and Soler (2001)	Clear	Diffuse
Souza and Robledo (2004)	Clear	Diffuse

3.2. Data sources

Data from two web sites were used to develop the models. The European database of daylight and solar radiation website, *Satel-light*, is used in this work to provide both irradiance and illuminance data, from which luminous efficacy for the selected locations is directly calculated (Satel-light, 2010). This data set covers the geographic area of Europe and parts of North Africa only. Data is available for the three main radiation types: global, direct and diffused incident for any defined surface orientation for the period 1996–2000. The second source is NASA Surface meteorology and Solar Energy (SSE) which has worldwide coverage. This was used to obtain data of independent variables such as hourly solar altitudes and cloud amount ratios (NASA, 2010).

There are other sources of satellite-based data. Solar altitude data required to generate luminous efficacy can be obtained from websites such as the MIDC SOLPOS application to calculate solar position (MIDC SOLPOS CALCULATOR, 2011). Irradiance data required to produce illuminance data can be obtained (free for year 2005, but from 1985 to 2004 on payment of fee) from the *SoDa* solar radiation data website (SODA, 2011). This site covers an area from −66° to 66° both in latitude and longitude. Global, diffused and direct data on horizontal surface and on surfaces tracking the sun at normal incidence are available.

Other independent variables such as sky clearness index, k_t, and sky brightness index, Δ, were estimated using published models. The k_t is given by the following formula (Woyte et al., 2007):

$$K_t = G_h / I_0 E_0 \sin\alpha \tag{2}$$

where I_0 is the extraterrestrial radiation = 1367 W/m^2; E$_0$ is the eccentricity correction factor of the Earth's orbit.

E_0 is computed according to Spencer's model (Spencer, 1971), which is chosen for the purpose of this study for its accuracy rather than Cooper's formula (Cooper, 1969) that used in the solar literature due to its simplicity (Almorox et al., 2005).

$$E_0 = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.00719\cos 2\Gamma + 0.000077\sin 2\Gamma \tag{3}$$

where the day angle Γ (radians) is given by:

$$\Gamma = 2\pi(n-1)/365(\text{radians}) \tag{4}$$

The sky brightness is given by Muneer and Angus (1993):

$$\Delta = I_d m / I_0 \tag{5}$$

where I_d is the diffused irradiance, I_0 is the extraterrestrial radiation, and m is relative optical air mass that can be approximated by Eq. (14) which gives satisfactory results for α angles from 30° to 90° (Nijegorodov and Luhanga, 1996).

Table 2
Global and diffused luminous efficacy models using independent variables other than solar altitude.

Model	Sky type	Light type	Input parameters
Olseth and Skartveit (1989)	Overcast	Diffuse	k_t, α
Perez et al. (1990)	All	Direct Global Diffuse	w, z, Δ[a]
Palz and Greif (1996)		Global Diffuse	α cc
Muneer and Kinghorn (1997)	All	Global Diffuse	k_t
Ruiz et al. (2001)	All	Global Diffuse	k_t
Robledo et al. (2001)	Overcast Intermediate	Global	α, Δ
Robledo and Soler (2001)	All Clear Intermediate Overcast	Diffuse	α, Δ

k_t: clearness index, Δ: brightness index, z: solar zenith angle, α: solar altitude, w: atmospheric precipitable water content, cc: cloud cover.

[a] In addition to 4 constants depending on k_t. Air temperature and humidity needed to estimate w.

$$m = 1/\sin\alpha \tag{6}$$

Instead it can be given by Eq. (15) according to Kasten and Young (1989):

$$m = [\sin\alpha + 0.50572(\alpha + 6.08)^{-1.6364}]^{-1} \tag{7}$$

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 3 lists the selected cities and their locations and altitudes, and the frequencies of occurrence of the characteristic sky conditions of the locations.

3.4. Statistical indicators

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

$$\mathrm{MBD} = \sum_{i=1}^{N} \frac{[(y_i - x_i)/x_i \cdot 100]}{N} \tag{8}$$

$$\mathrm{RMS} = \left[\sum_{i=1}^{N} \frac{[(y_i - x_i)/x_i \cdot 100]^2}{N}\right]^{1/2} \tag{9}$$

$$\mathrm{MAD} = \sum_{i=1}^{N} \frac{(|y_i - x_i|/x_i \cdot 100)}{N} \tag{10}$$

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. The MBD indicates a measure of the overall trend of a given model, i.e. overestimating (positive values) or underestimating (negative values). MAD and RMS offer measures of absolute deviation.

3.5. Luminous efficacy generation

Global and diffuse horizontal illuminance and irradiance data was obtained from Satel-light in the form of monthly means of hourly values for ten 'originating' locations. From each the global and diffused horizontal 'reference luminous efficacy' (K_g and K_d, respectively) were calculated using Eq (1). Table 3 lists the maximum, minimum and mean reference values for each location, excluding values corresponding to solar altitude less than 1°.

In the global case, it is clear that the maximum values are very similar, with a slight decrease in the Southern locations. The minimum and mean values are almost identical. The averages of the maximum, minimum and mean global reference values are 114 lm/W, 101 lm/W and 111.4 lm/W, and of the diffused values are 132 lm/W, 111 lm/W and 123 lm/W respectively.

Table 3
Locations frequencies of sky conditions and Luminous Efficacy.

City		Location Conditions		Sky Conditions (%)			K_g (lm/W)			K_d (lm/W)		
		Lat (°N)	Lon (°E)	Sun	Intermed.	Overcast	Max.	Min.	Mean	Max.	Min.	Mean
Copenhagen	DK	56	13	34	38	28	115	100	111	150	100	120.2
Moscow	RU	56	38	35	40	25	115	100	111	127	100	121.2
London	UK	51	0	31	42	27	116	100	112	130	116	122.1
Kiev	UA	50	31	38	35	27	115	100	111	130	118	123.9
Bordeaux	FR	45	1	47	34	19	115	100	112	135	117	127.1
Bucharest	RO	44	26	49	31	20	114	100	111	128	100	120.5
Valencia	ES	39	0	70	20	10	114	103	111	129	100	121.8
Athena	GR	38	24	68	21	11	113	100	112	130	119	124.0
Nador	MA	35	03W	67	24	9	114	100	111	126	118	121.9
Khania	GR	36	24	69	19	12	113	105	111	139	121	127.0

Cloudy sky: sky condition corresponding to cloud index larger than 0.6, intermediate sky: cloud index larger than 0.15 and smaller than 0.6, sunny sky: cloud index smaller than 0.15.

4. Global luminous efficacy

4.1. Development of the proposed global models

4.1.1. Model developed from solar altitude

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

$$K_{g1} = -0.0034\alpha^2 + 0.358\alpha + 104.17 \tag{11}$$

In Eq. (11), the lower threshold of luminous efficacy for values corresponding to $\alpha \geqslant 55$ may be assumed equal to the average maximum K_g of 114 lm/W. This assumption can be properly, but not necessarily, taken into account as the difference it makes was found to be insignificant.

4.1.2. Model developed from solar altitude and cloud amount

Cloud amount, C, the monthly averaged cloud amount at indicated GMT times (%), was used as a weighting parameter to investigate its effect over the luminous efficacy-solar altitude relationship. Cloud amount was used by Kasten and Czeplak (1980) to give typical values of the different radiation quantities in different cloud conditions. A modified version of this model was suggested by Muneer et al. (2000) and in the first part of this work, cloud amount was used as a weighting parameter by either dividing or multiplying solar altitude by cloud amount. The relationship between the these values and luminous efficacy investigated whether including the cloud amount, as a meteorological parameter affect the radiation amount reaches earth's surface, could improve the estimation of luminous efficacy. In Fig. 2, the values obtained for C/α was plotted against K_g for the ten originating locations giving an almost linear relationship. The best fit curve expressed as follows:

$$K_{g2} = 0.0513(C/\alpha)^2 - 1.3843C/\alpha + 114.28 \tag{12}$$

In Eq. (12) the lower threshold of luminous efficacy for values corresponding to $(C/\alpha) \geqslant 13.5$ (applicable to $\alpha \leqslant 5°$) to be equal to the average minimum K_g of 101 lm/W.

4.1.3. Model developed from sky clearness index

The clearness index, k_t, is defined as the ratio of the global radiation at ground level on a horizontal surface and the extraterrestrial global solar irradiation. Muneer and Kinghorn (1997) concluded that the clearness index is the key parameter in the prediction of luminous efficacy since it appears to cause the greatest variation in global efficacy, and thus it was investigated in this study. The variation of K_g plotted against the k_t for all ten originating locations. Fig. 3 shows the best fit polynomial curve, which is as follows:

$$K_{g3} = -44.008k_t^2 + 50.826k_t + 97.82 \tag{13}$$

Fig. 3 is similar to the Muneer and Kinghorn model using local coefficients as validated by Souza et al. (2006).

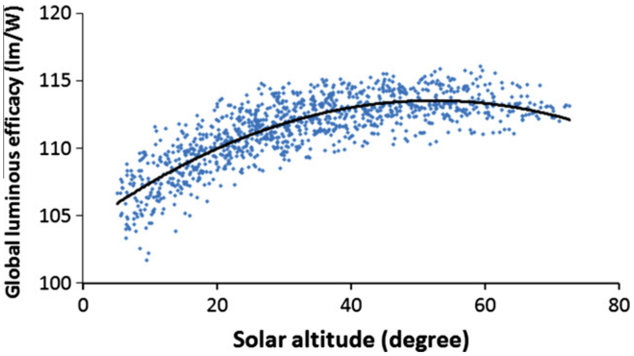

Fig. 1. Global luminous efficacy plotted against solar altitude.

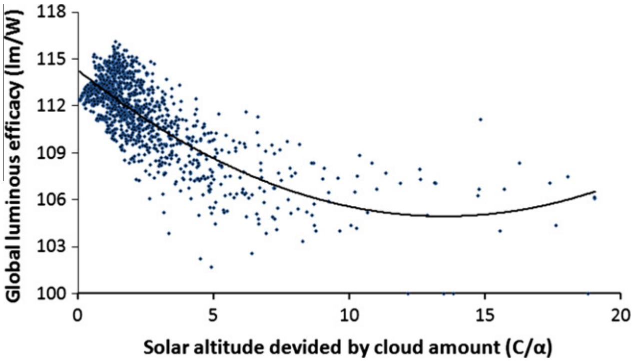

Fig. 2. Global luminous efficacy plotted against solar altitude and cloud amount (C/α).

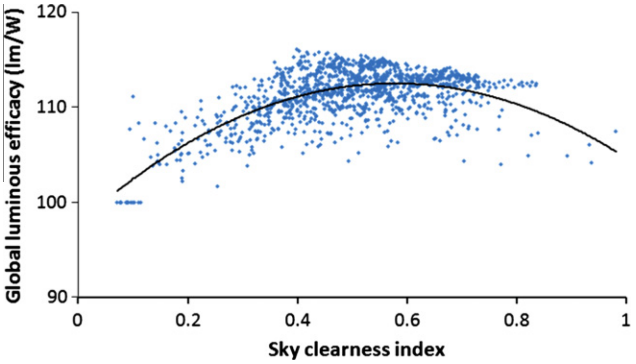

Fig. 3. Global luminous efficacy plotted against clearness index.

4.2. Statistical performance of the proposed global models

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

• Oslo (NO)	Lat. 60°N, Long. 11°E
• Berlin (DE)	Lat. 52°N, Long. 13°E
• Parma (IT)	Lat. 45°N, Long. 10°E
• Alger (DZ)	Lat. 37°N, Long. 3°E

Fig. 4 shows the statistical performance of the models described by Eqs. (11)–(13), named Mg-1, Mg-2 and Mg-3 respectively. The statistical performance of the developed models showed good agreement between originating and validation locations. The results show a slight superiority of Mg-1 over both Mg-2 and Mg-3 in terms of MAD and RMS, and very similar results in terms of MBD for either location. Mg-1 had the statistical performance averages MAD = 1.1%, RMS = 1.5% and MBD = 0%, for the originating locations and MAD = 1.1%, RMS = 1.4% and MBD = 0% for the validation locations. Originating and validation location performances thus showed good agreement. Mg-1 is more stable than the other two models which is derived from the variations of the statistical indicators over the fourteen locations. The differences for Mg-1 between minimum and maximum values of MAD, RMS and MBD are 0.7%, 0.9% and 2.3% respectively, compared with 1.4%, 1.1% and 3.4% for Mg-2, and 1.5%, 1.8% and 2.5% for Mg-3. It is worth noting that underestimation of luminous efficacy tends to occur in the more northerly locations studied.

Fig. 5 shows the estimated efficacy values calculated using the models. Comparison between the averages of the reference and estimated efficacies show differences between the maximum values are 1.4, 0.9 and 2.4 lm/W for Mg-1, Mg-2 and Mg-3 respectively. The average

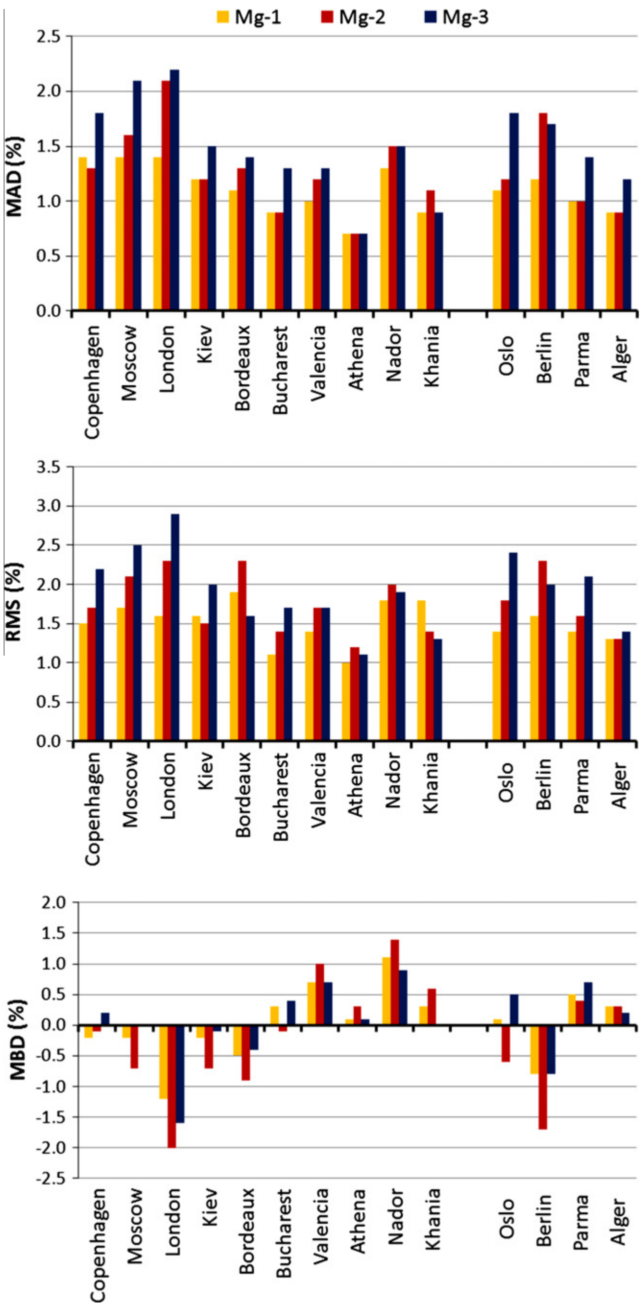

Fig. 4. Statistical assessment of global developed models.

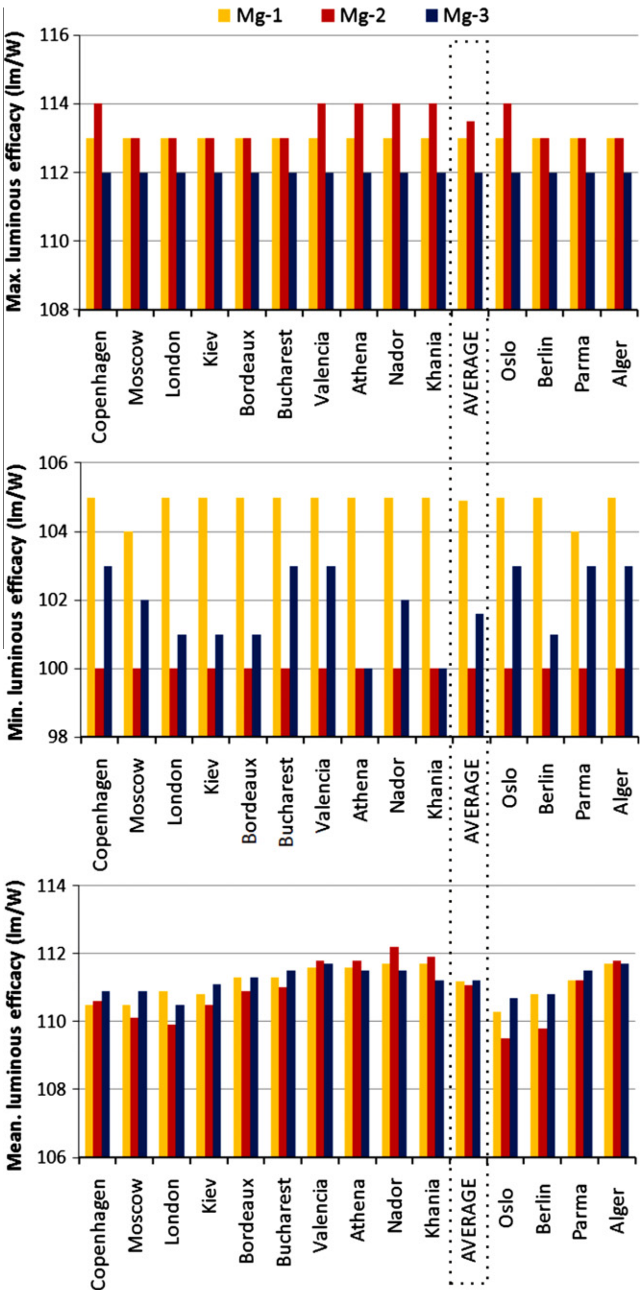

Fig. 5. Estimated global luminous efficacy values (lm/W) using developed models.

minimum of Mg-1 is 4 lm/W more than the reference, while it is ±0.8 lm/W for Mg-2 and Mg-3. The differences between the average mean values for all models are negligible at 0.1–0.2 lm/W. The differences between the models in terms of maximum and mean values are insignificant.

The differences between the ‘estimated efficacies values’ suggest that all models could potentially be used for estimation purposes. However the statistical performance tends to favour model Mg-1 which also has the additional benefit of simplicity.

4.3. Published global models

The models indicated in Tables 1 and 2 are those commonly cited in the literature. All of the models mentioned in those Tables 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 global luminous efficacy on horizontal surface were:

4.3.1. Ullah (Ullah, 1996)

The author expresses the correlated global luminous efficacy solely to the solar altitude for clear skies as a fourth degree polynomial of α. The following formula based on a measured data from Singapore:

$$K_{g4} = 107.3311 + 1.14157\alpha - 0.0422882\alpha^2 + 0.539488 \times 10^{-3}\alpha^3 - 0.234698 \times 10^{-5}\alpha^4 \quad (14)$$

4.3.2. Muneer et al. (Muneer and Kinghorn, 1997)

This model is for all skies types. The authors express the correlated global luminous efficacy solely to the clearness index as a second degree polynomial of k_t. The following formula based on a measured data from five sites in the UK:

$$K_{g5} = 136.6 - 74.541k_t + 57.3421k_t^2 \quad (15)$$

4.3.3. Ruiz et al. (Ruiz et al., 2001)

This model is for all skies types. The authors correlated the global luminous efficacy to the sinus of solar altitude and to clearness index. The following formula based on a measured data from Madrid:

$$K_{g6} = 104.83(\sin\alpha)^{0.026}k_t^{-0.108} \quad (16)$$

4.4. Statistical performance of the published global models

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

Table 4 reports the average statistical performance of the estimated values from the published models. In terms of MAD indicator, Ruiz’s model is the best performer with average of 3.4% against 4.1% for each of the other models, and the lowest maximum of 3.8% compared with 4.6% and 5.9% for Ullah’s and Muneer’s models respectively. Both Ruiz’s and Ullah’s had a similar stability at around 1%, against 3.4% for Muneer’s. The RMS indicator illustrates that the average performance of both Ruiz’s and Ullah’s is 5.1%, against 6.5% for Muneer’s, and the lowest maximum is around 5.8% for the first compared with 8.3% for the latter. Ruiz’s and Ullah’s showed a similar stability around 1.5% against 3.4% for Muneer’s. Since the MBD indicator has positive and negative values, the average performance and the lowest maximum values may be misleading, and thus the stability value is considered to be best described in terms of MBD. Ullah’s comes first with stability of 2.1%, then Ruiz’s with 3.8% and Muneer’s with 4.7%.

Comparison between the averages of each of the reference and estimated efficacies values, estimated using the published models, shows the following. The maximum value for Ullah’s model is 3 lm/W more than the reference, which is much better than the 18 lm/W and 13 lm/W achieved respectively by Muneer’s and Ruiz’s models. Ruiz’s minimum and mean differences are best with values of 0 lm/W and 0.4 lm/W respectively; compared with the 7 lm/W and 2.8 lm/W achieved by Ullah’s, or 11 lm/W and 3.8 lm/W achieved by Muneer’s.

The above suggests that Ruiz’s model is the best in estimating illuminance data from satellite irradiance data.

4.5. Comparison of the global models

Statistical performances and differences between reference and estimated luminous efficacies over the fourteen locations were used to compare developed and published

Table 4
Average statistical performance of all global models over the originating and validation locations.

Models		MAD (%)	RMS (%)	MBD (%)	K_g differences		
					Max	Min	Mean
Mg-1	(Eq. (11))	**1.1**	**1.5**	**0.0**	**−1**	4	−0.2
Mg-2	(Eq. (12))	1.3	1.8	−0.2	−1	−1	−0.4
Mg-3	(Eq. (13))	1.5	1.9	0.1	−2	1	**−0.1**
Constant	111.4	2.0	2.7	0.3	–	–	–
Ullah	(Eq. (14))	4.1	4.8	2.7	3	7	2.8
Muneer	(Eq. (15))	4.1	6.5	3.5	18	11	3.8
Ruiz	(Eq. (16))	3.4	5.1	0.5	13	**0**	0.4

models, and a constant luminous efficacy of 111.4 lm/W representing the average of the mean efficacies values for the originating locations. This derived constant value compares with the value of 110 lm/W suggested by De Rosa et al. (2008).

Table 4 shows that Mg-1 has the best statistical performance among the developed models, that of Ruiz among those published, and the constant value somewhere between the two. The statistical indicators suggest that Mg-1 performs more than three times better than Ruiz's model, the best published one, and around twice that of the constant value (see Fig. 6). The MAD indicator shows that Mg-1 ranges around 1.1% with stability of 0.7%, whilst the constant value ranges around 2% with stability of 1.5%, and Ruiz's ranges around 3.4% with stability of 1%. In terms of RMS, 1.5%, 2.7% and 5.1% are the ranges of Mg-1, constant value and Ruiz's respectively, with stabilities of 0.9%, 1.4% and 1.4%. The MBD indicator tells that the constant value is the most stable one with a difference of 1.6% compared with 2.3% and 2.9% for Mg-1 and Ruiz's respectively.

4.6. Application of the proposed and published global models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data for the locations listed below. All of this data has previously been used in published works, which contain details of data collection and quality control (Li and Lam, 2000; De Rosa et al., 2008; Muneer and Kinghorn, 1998; Markou et al., 2007; Skartveit and Olseth, 2000; Satel-light, 2011).

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

The proposed model that included cloud amount (Mg-2) could not be tested since the measured data did not include simultaneous cloud amounts. The statistical performance of Mg-1, all published models and the constant value (see Table 5) shows that no single model performs best over all locations. The constant value is best for Bratislava and Hong Kong, closely followed by Mg-1 (less than 0.5%). Muneer's model is best for Edinburgh and Fukuoka, and Ruiz's for Arcavacata. Although Ullah's model did not perform best in any location, its average performance over the five locations compares well with the constant value. Both have the following five-location averages; MAD = 9.9%, RMS = 13.8%, with MBD = −1.1% for the constant value and 1% for Ullah's. Mg-1 came next with not more than 0.2–0.3% difference for each of the statistical indicators. Muneer's model was next with five-location averages of 10.4%, 14.4% and 5.2% for the MAD, RMS and MBD respectively, and finally Ruiz with 1–2% difference between its averages and the best performance over all the statistical indicators (see Fig. 7).

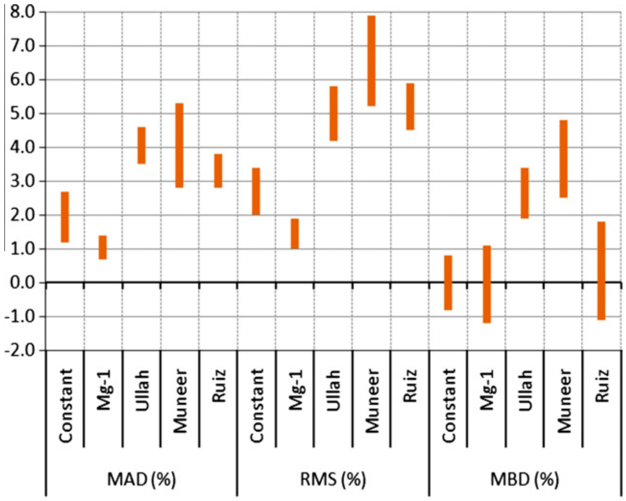

Fig. 6. Statistical indicators ranges of the constant value and global developed and published models.

Though the differences between the statistical performance of Mg-1, the constant value and Ullah's model are insignificant, Mg-1 and the constant value show more stability than Ullah's; with values of 8.7% and 11% for the MAD and RMS respectively compared with 11.1% and 13.3% for Ullah. Mg-1, the constant value and Ullah's exhibit a similar stability in terms of MBD at around 21.7%. Muneer's and Ruiz's stabilities are 2–6.5% more than Mg-1 for all the indicators.

The previous comparison shows that constant value of 111.4 lm/W gives the best performance along with model Mg-1, the second degree polynomial formula of solar altitude solely, followed by Ullah's model. Muneer's and Ruiz's models have been developed to predict global luminous efficacy under all skies types, the former is a second degree polynomial formula derived solely from the clearness index, and the later is a power formula using the sine of solar altitude and clearness index. They are both more complicated than the alternatives, tend to overestimates luminous efficacies values, and are much less stable than Mg-1.

5. Diffused luminous efficacy

5.1. Development of the proposed diffused models

5.1.1. Model developed from solar altitude

Using solar altitude 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. Fig. 8 shows the best fit curve, which is as follows:

$$K_{d1} = 0.0164\alpha + 122.74 \tag{17}$$

5.1.2. Model developed from solar altitude and cloud amount

Cloud amount used as a weighting parameter to investigate its effect over luminous efficacy-solar altitude relation-

Table 5
Average statistical performance of proposed and published global models.

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Hong Kong		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
Mg-1	6.6	9.0	−5.1	8.5	12.4	**0.4**	8.9	15.0	−2.6	11.6	13.9	−10.5	15.3	19.8	11.5
Constant	6.3	8.4	−4.8	**8.1**	**12.1**	0.7	8.7	14.8	−2.1	11.6	13.6	−10.6	**15.0**	**19.5**	**11.1**
Ullah	5.4	7.8	−2.5	9.0	13.0	3.3	8.2	15.1	0.6	9.9	12.0	−8.8	16.4	21.1	12.7
Muneer	**4.1**	**6.1**	**0.6**	12.8	17.7	11.0	**8.0**	15.0	3.0	**7.9**	**9.8**	**−6.2**	19.1	23.6	17.6
Ruiz	5.0	6.9	−2.6	15.2	22.3	12.6	8.4	**14.3**	**−0.5**	9.6	11.5	−8.6	17.2	22.0	15.6

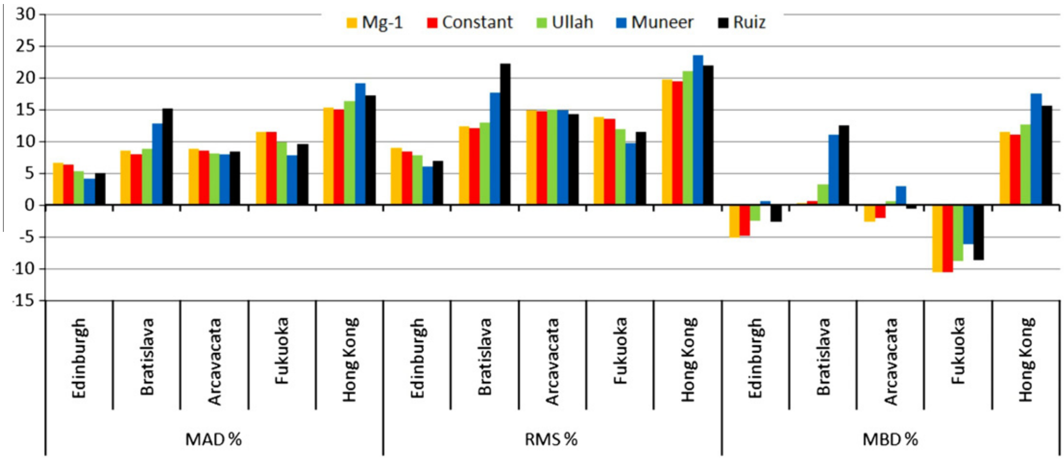

Fig. 7. Comparison between global models statistical performance.

ship. In Fig. 9, the values obtained for α (*1-C*) was plotted against K_d for the ten originating locations. The best fit curve expressed as follows:

$$K_{d2} = 114.1(\alpha(1 - C))^{0.109} \tag{18}$$

5.1.3. Model developed from sky clearness index

The variation of K_d plotted against the k_t for all ten originating locations. Fig. 10 shows the best fit curve, which is as follows:

$$K_{d3} = 29.492k_t^3 - 18.305k_t^2 + 3.5567k_t + 121.83 \tag{19}$$

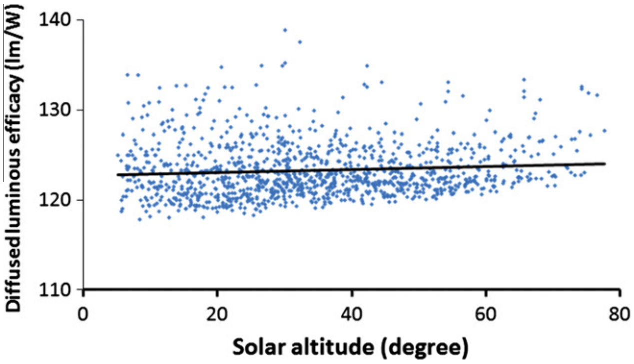

Fig. 8. Diffused luminous efficacy plotted against solar altitude.

5.2. Statistical performance of the proposed diffused models

Statistical assessment similar to that carried out with the global case has been carried out with the diffused case to identify the best performing proposed model.

Fig. 11 shows the statistical performance of the models described by Eqs. (17)–(19); namely Md-1, Md-2 and Md-3. The statistical performance of the developed models shows agreement between the originating and validation locations. The results show slight superiority of Md-3 over both Md-1 and Md-2 in terms of MAD and RMS, and very similar results in terms of MBD for both originating and validation locations (see Table 6). Md-3 has the following statistical performance averages: MAD = 1.6%, RMS = 2.2% and MBD = 0%, from the ten-originating locations, and MAD = 1.4%, RMS = 1.9% and MBD = 0.3% from the four-validation locations. Thus, the originating and validation location performances show a good agreement. Md-3 performance is more stable than the other two models in terms of MBD, but very similar to them in terms of MAD and RMS. This is apparent from the variations of the statistical indicators over the fourteen locations. The differences between minimum and maximum values of MAD, RMS and MBD for Md-3 are 1.4%, 2% and 3.5% respectively, compared with 1.9%, 2.6% and 5% for Md-1, and 1.3%, 1.7% and 4.5% for Md-2. It is worth mentioning that underestimation of luminous efficacy tends to occur in the Southern locations.

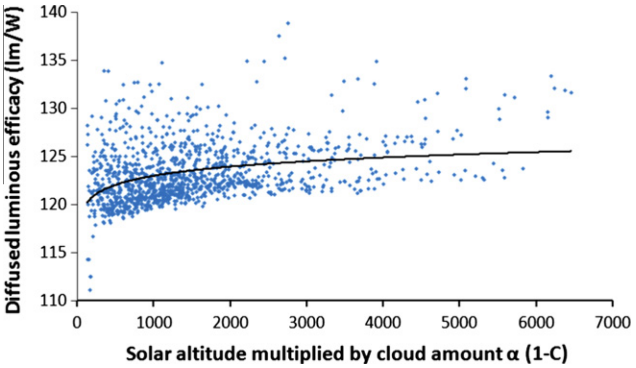

Fig. 9. Diffused luminous efficacy plotted against solar altitude and cloud amount ($\alpha(1-C)$).

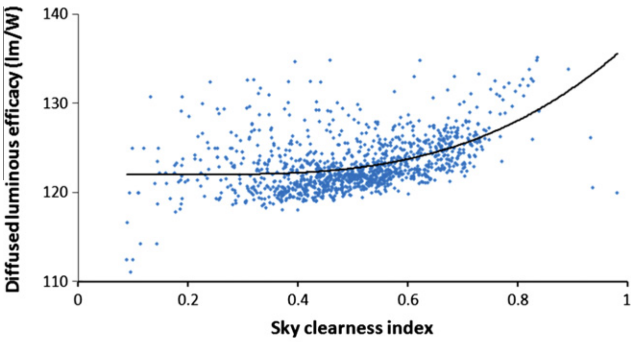

Fig. 10. Diffused luminous efficacy plotted against clearness index.

Fig. 12 shows the estimated efficacies values calculated using the developed models. Comparison between the averages of reference and estimated efficacies values shows that the differences between the maximum values are 8, 8 and 4 lm/W for Md-1, Md-2 and Md-3 respectively, and between the minimum values are −12, −7, −11 lm/W. Negligible difference of 0.1–0.2 lm/W are noted between the average mean values for all models. The differences between the models in terms of maximum and minimum values are significant, whilst those in terms of mean values are negligible.

Although the statistical performance tends to favour Md-3 model, the simplicity of Md-1 makes it a practically useful since the differences are small. In terms of 'estimated efficacy values' no one model stands out.

5.3. Published diffused models

All of the models mentioned in Tables 1 and 2 were evaluated using satellite data and those that gave the best results used for comparison with the proposed models. Some of the published models with many variables were excluded for this purpose since as one of the aims of this work was to generate simple models using widely available parameters only. The models considered for estimation of the diffused luminous efficacy on horizontal surface were:

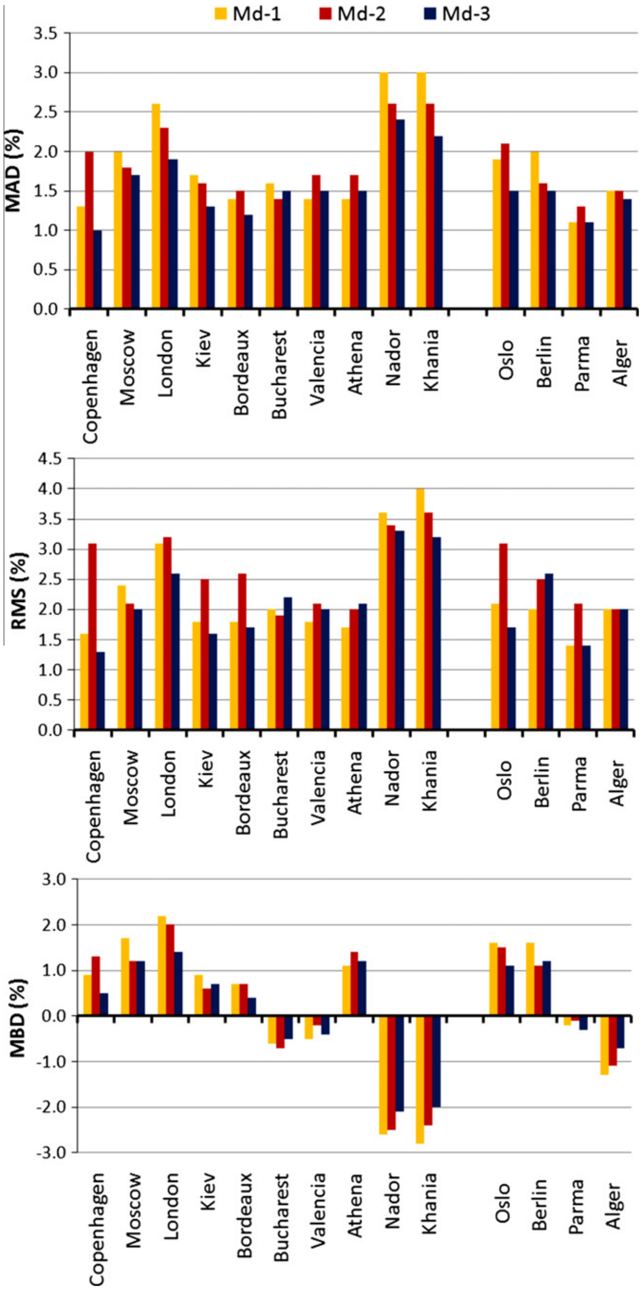

Fig. 11. Statistical assessment of diffused developed models.

5.3.1. Muneer et al. (Muneer and Kinghorn, 1997)

This model is for all skies types. The authors express the correlated the K_d solely to the clearness index as a second degree polynomial of k_t. The following formula based on a measured data from five sites in the UK:

$$K_{d4} = 130.2 - 39.828k_t + 49.9797k_t^2 \tag{20}$$

5.3.2. Robledo et al. (Robledo and Soler, 2001)

The authors correlated the K_d to the sinus of solar altitude and to sky brightness index Δ. A model developed with different coefficients for clear, intermediate and overcast skies, in addition to coefficient for all skies. The fol-

Table 6
Average statistical performance of all diffused models over all originating and validation locations.

Models		MAD (%)	RMS (%)	MBD (%)	K_g differences		
					Max	Min	Mean
Md-1	(Eq. (17))	1.9	**2.2**	**0.2**	8	−12	**−0.2**
Md-2	(Eq. (18))	1.8	2.6	**0.2**	8	−17	**−0.1**
Md-3	(Eq. (19))	**1.6**	**2.1**	**0.1**	4	−11	**−0.2**
Constant	123	1.8	2.3	**0.2**	–	–	–
Muneer	(Eq. (20))	1.9	3.3	0.7	**2**	−11	−0.7
Robledo	(Eq. (21))	5.6	7.6	4.9	24	**0**	−5.9

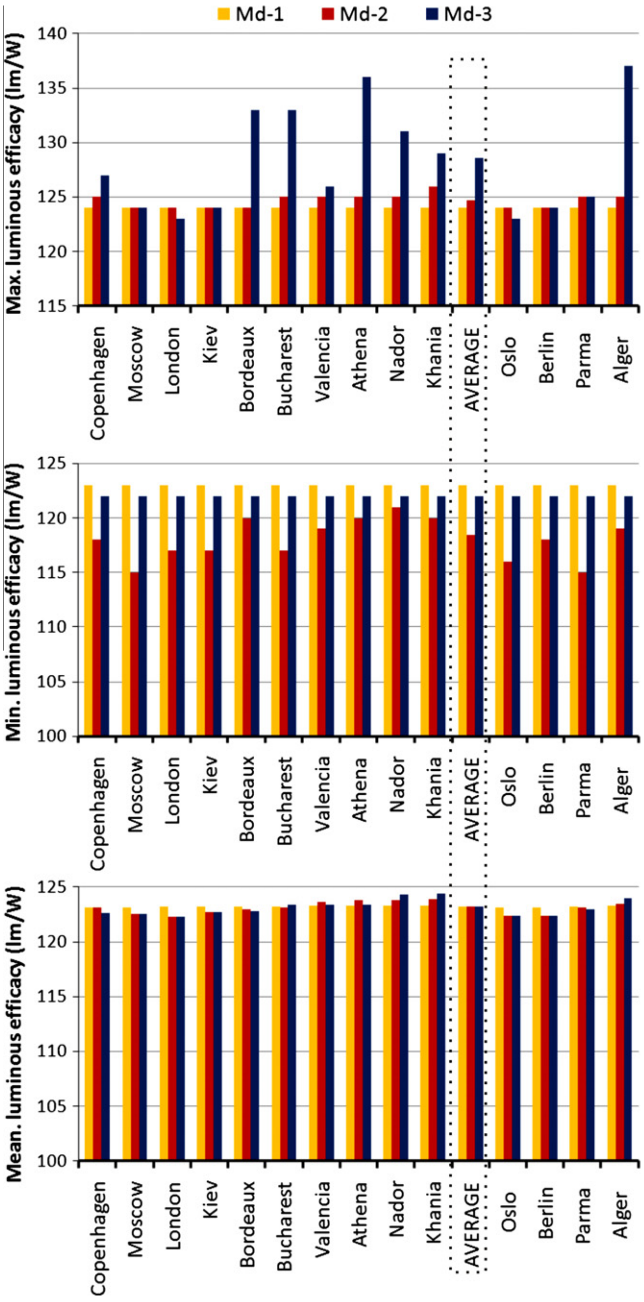

Fig. 12. Estimated Diffused luminous efficacy values (lm/W) using developed models.

lowing formula for all skies based on a measured data from Madrid, and thus coefficients may change somewhat for other locations; as stated by the authors (Robledo and Soler, 2001):

$$K_{d6} = 82.24(\sin\alpha)^{-0.034}\Delta^{-0.266} \tag{21}$$

5.3.3. Ruiz et al. (Ruiz et al., 2001)

This model is for all skies types. The authors correlated the K_d to the sinus of solar altitude and to diffused clearness index k_d. The authors suggest that for diffuse illuminance estimation the ratio of diffuse to extraterrestrial irradiance is to be preferred as independent variable to the ratio of global to extraterrestrial irradiance used in Muneer's Model (Muneer and Kinghorn, 1997). The following formula based on a measured data from Madrid:

$$K_{d6} = 86.97(\sin\alpha)^{-0.143}k_d^{-0.218} \tag{22}$$

5.4. Statistical performance of the published diffused models

The published models have been used, as well as the developed models, 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.

Comparison between Ruiz's model and the other two lead to it being rapidly dismissed. Its MAD, RMS and MBD are much inferior to the other two models. Muneer's model obtained averages of 1.9%, 3.3% and 0.7% for MAD, RMS and MBD respectively compared with 5.6%, 7.6% and 4.9% for Robledo's (see Table 6). Both showed a similar stability at around 1.4% and 2.2% for MAD and RMS respectively, whilst in terms of MBD Robledo's achieved stability of 1.9% against 3.6% for Muneer.

Comparison between the averages of each of the reference and estimated efficacies values, estimated using the published models, shows 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 of 0.7 and −5.9 lm/W (see Table 6).

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.

5.5. Comparison of the diffused 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 123 lm/W. The derived constant value is equal to that suggested by De Rosa et al. (2008).

From Table 6 it can be noticed that among the developed models Md-3 shows the best statistical performance by a very slight margin. The best performing published models is clearly Muneer's in Table 6. The constant value gave the same average performance as the developed models. Taking the statistical performance into account, the MAD indicator for any of Muneer's model, the constant value and the developed models is about the same. Muneer's RMS is 1% more than them, and its MBD is only 0.5% ahead. Fig. 13 illustrates the similarity of the constant value, Md-1, Md-3 and Muneer's model, and the difference between them and Robledo's model. The MAD indicator shows values of around 1.9% for all of them apart from Robledo's is around5.6% with best stability of 1% for Muneer's. In terms of RMS, 2.3% is the range 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 Md-3. The MBD indicator indicates 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.

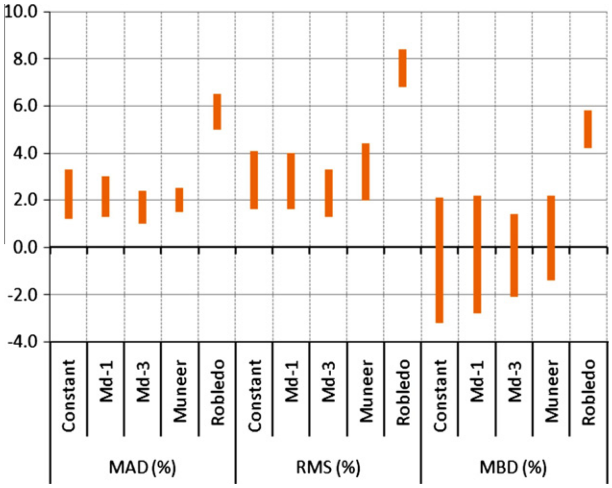

Fig. 13. Statistical indicators ranges of the constant value and Diffused developed and published models.

Estimated efficacies values by the developed models gave means exhibiting negligible differences with the reference mean with Muneer's model showing a 0.7% difference and Robledo's a large difference of 5.9%.

5.6. Application of the proposed and published diffused models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data from the locations previously mentioned in Section 4.6. The proposed model that included cloud amount (Md-2) could not be tested since the measured data did not include simultaneous cloud amounts.

The statistical performances of the developed models Md-1 and Md-3, and the published Muneer's and Robledo's models, in addition to the constant value 123 lm/W, are as presented in Table 7, which shows that Robledo's model exhibits the best performs in Fukuoka only. The performances of all the others are generally close with differences between any two indicators generally not exceeding 1.3% (see Fig. 14). Md-3 performs best in Edinburgh, joint top in Hong Kong (with the constant value), in Bratislava (with Md-1), and in Arcavacata with (Muneer's model) (see bold values in Table 7). In terms of average performance over all locations, the MAD for all of them is 11.5–11.8%, but Robledo's is 17.8%. The RMS is 14.3–14.6% and 25.1% for Robledo's.

Robledo's model shows a lack of stability with values of 20%, 33% and 40% for MAD, RMS and MBD respec-

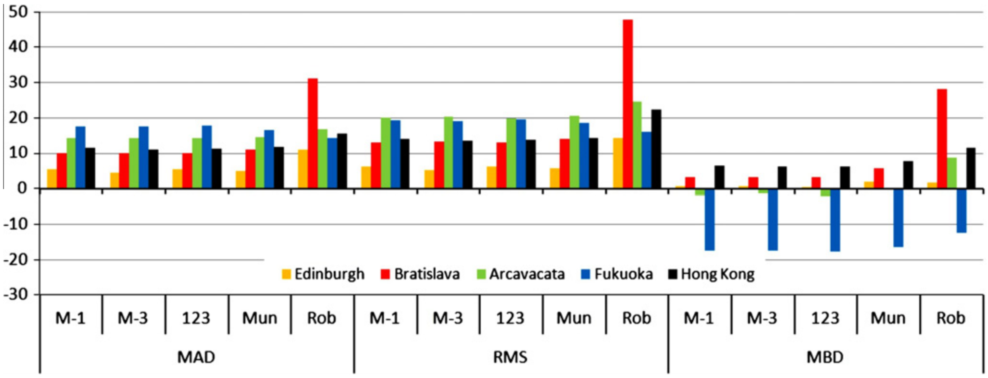

Fig. 14. Comparison between Diffused models statistical performance.

Table 7
Average statistical performance of proposed and published diffused models.

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Hong Kong		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
M-1	5.4	6.2	**0.7**	**10.1**	**13.0**	**3.3**	**14.4**	**20.0**	−1.9	17.5	19.4	−17.5	11.4	14.0	6.6
M-3	**4.6**	**5.3**	**0.8**	**10.1**	**13.2**	**3.2**	**14.4**	**20.2**	−1.2	17.5	19.2	−17.4	**11.0**	**13.6**	**6.4**
Constant	5.4	6.2	**0.6**	**10.0**	**13.0**	**3.1**	**14.4**	**19.9**	−2.1	17.7	19.6	−17.7	**11.2**	**13.8**	**6.2**
Muneer	5.1	5.7	1.9	11.1	14.0	5.7	**14.6**	20.5	**0.2**	16.6	18.5	−16.5	11.7	14.3	7.7
Robledo	11.0	14.3	1.7	31.2	47.8	28.1	16.8	24.7	8.7	**14.4**	**16.1**	**−12.4**	15.5	22.4	11.6

tively. The others have similar stabilities. In terms of MAD, the range is 11.5–12.9% with Muneer's the best. The range of RMS is 13.7–15% with Md-1 and the constant value best. The MBD range is 23.8–24.2%; Md-3 and the constant value perform best.

The previous comparison shows that constant value of 123 lm/W gives the best performance along with the developed models Md-1, and Md-3, in addition to Muneer's model. Given very close results, they may be ranked according to their simplicity as: constant value first, the linear formula of solar altitude Md-1 next, and the polynomial formulas of clearness index Md-3, and finally Muneer's model.

6. Conclusion

Design processes of daylighting systems face barriers of lack of measured daylight data. Therefore, conversion of the much more widely available irradiance data emerges as acceptable way to obtain illuminance data using the concept of luminous efficacy. A number of models and constant values suggested in solar literature to estimate luminous efficacy; based variously on the relation between luminous efficacy and solar altitude and/or meteorological parameters. Some of them require more extensive data to calculate local coefficients, which is a limiting factor in their wider applicability.

The new approach was developed using satellite irradiance and illuminance data for ten locations in Europe and North Africa. Further four locations in the same region have been used for validation. The proposed models were developed from the relation between the luminous efficacy and any of solar altitude, cloud amount or sky clearness index. Among the proposed models, the models based on solar altitude, Mg-1 and Md-1, emerged as the simplest and best statistically performing models over the fourteen locations. In compare with the published models, the statistical performance of Mg-1 is up to three times more accurate than the best performing published global models, Ruiz's model. The global constant value showed better statistical performance than the published models, but Mg-1 still twice as good as illustrated in Table 4. Md-1 performance is up to 1.5 times more accurate than the best performing published diffused models, that of Muneer. The diffused constant value achieved similar performance to Md-1.

In the final part of the work, the constant values, the published and proposed models were used to estimate illuminance data for five locations for which actual global and diffused irradiance, global and diffused illuminance, and solar altitude data was available. The statistical indicators showed that Mg-1 and the global constant value slightly produce more accurate estimates of global luminous efficacy than the published models, but without the use of extensive local data (see Table 5). Meanwhile, all of the diffused constant value, Md-1 and Muneer's model produce very close estimates of the diffused luminous efficacy.

Therefore, simplicity points out the constant value as the most favourable method.

The constant values and models were validated over 19 locations extending from 22°N to 60°N, and from 0° to 130°E, but further validation of the method awaits the production of measured data from outside this locations area. In general the modelled data tends to follow a trend, while measured data is subject to the natural variations. Thus differences between produced illuminance values and measured values are bigger than the difference between produced illuminance values and modelled values.

This work suggests new methods of estimation of horizontal global and diffused luminous efficacies based on satellite data which is widely available, free of charge, on web servers. The resulting methods are constant values or universal models 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. Because local conditions can be a major influence on illuminance value, measured data is recommended for design purposes where it is available. For geographic regions where measured data is not available the satellite based approach to generation of illuminance data is likely to become increasingly important for design purposes.

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