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A model to estimate direct luminous efficacy based on satellite data

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Abstract

This paper presents a universal model of luminous efficacy for direct solar radiation on a horizontal surface. The model is applicable to all sky conditions and is based on data obtained from satellites and available via web servers. Solar radiation data from 10 locations in Europe and North Africa has been used to obtain four functions for luminous efficacy (K) against the sole independent variable solar altitude (α). Additionally cloud amount (C) was been used to obtain four other functions. All were used to accurately estimate illuminance for the 10 originating locations; for four locations based on satellite data; and for a further four based on measured data. A statistical assessment showed that three models performed best, namely, K against $1/\alpha$, K against $\sin\alpha$, and K against C/α. Comparison between results from the proposed models, and those produced using three previously 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; Illuminance; Irradiance; Satellite

1. Introduction

Electric lighting is dominant in the majority of modern buildings and offers the opportunity to create an attractive and economic lit interior within any building configuration. Since electric lighting is a major energy consumer there is a case for the provision of daylight as a substitute. Also research has confirmed user preference for daylight in working interiors which has implications for user satisfaction and well-being. Taken together this makes the provision of daylight a powerful design aspiration for modern buildings (Boyce, 1998).

Over the last few years the development of 'daylight guidance systems' has made redirection of zenithal daylight into areas remote from the building envelope a practical possibility. Since the systems use as a source, variously, combinations of sunlight and skylight at different orientations, a detailed knowledge of illuminance conditions at potential locations is necessary in order to assess their feasibility (Mayhoub and Carter, 2009). Unfortunately there is a general dearth of measured daylight data suitable for this task. In the UK for example there are less than 10 sites measuring global horizontal illuminance in contrast to over 600 measuring meteorological data including solar irradiance. Luminous efficacy models 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

$$K = E/I \ (\mathrm{l\,m/W}) \tag{1}$$

Although this work has its origins in a study of daylight guidance systems, the techniques described allow

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generation of data for design or analysis of any daylight device. The unique features of daylight guidance collection devices means that illuminance on horizontal, or near horizontal surfaces is more important than that incident on vertical surfaces. Guidance systems employing high daylight concentration ratios (for example hybrid systems) use the direct component only, while systems of low concentration ratios (notably tubular systems) also use considerable amounts of direct illuminance. For this reason in this work the attention will be focused on generating information on direct illuminance on horizontal surface. Future work will assess illuminance on inclined surfaces, and global and diffused illuminance.

2. Review of luminous efficacy models

2.1. Model classification

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 (details in Table 1). The second group uses one or more of *solar zenith angle*, *amount of water vapour*, *clearness index*, *brightness index*, *relative optical air mass and atmospheric turbidity factors* as independent variables. In addition *solar altitude* is used in some cases (see Table 2). The last group uses *constant values* without any variables.

2.2. Model characteristics

The majority of models listed in Table 1 are based on polynomial expressions of different degrees functions of solar altitude. They thus could be considered to be one model with the addition of local climatic coefficients. The Robledo and De Souza exponential models are examples of the latter for Madrid and Florianopolis, respectively (Robledo and Soler, 2000; De Souza et al., 2005) The majority of models employing solar altitude as the only independent variable are specific to sky type and location.

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. A number of studies have been carried out seeking to prove their universal applicability. Muneer, commenting on the validation studies to test this claim, concluded that none were able to do this (Muneer, 1997).

The third group advance constant values for luminous efficacy for each of global, diffuse and direct irradiance. De Rosa claims that its method universally “behaves well and furnishes good results in spite of its simplicity in all skies” (De Rosa, 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.

2.3. Previous methodologies

Three methodologies for estimating luminous efficacy emerge from the literature. The first makes use of either the available meteorological data, or the measured irradiance and corresponding illuminance data, in specific locations in order to develop a model. The second employs measured data to validate an established model often with the development of new local coefficients. The last uses an established model to generate illuminance values for new location.

Table 1
Direct luminous efficacy models using solar altitude as the only independent variable.

Model, 1st author (year)	Sky type	Light type	Data location
Aydinli and Krochmann (1983)	Clear	Direct	Theoretical spectral attenuation data
Littlefair (1988)	Clear	Direct Diffuse Global	Empirical data from Garston, UK
	Overcast	–	
	Intermediate	Global	
Chung (1992)	Clear	Direct Diffuse Global	Empirical data from Hong Kong
	Overcast	–	
	Intermediate	Global	
Ullah (1996)	Clear	Direct Diffuse Global	Empirical data from Singapore
	Overcast	–	
	Intermediate	Global Diffuse	
Robledo and Soler (2000)	Clear	Direct	Empirical data from Madrid, Spain
De Souza et al. (2005)	Clear	Direct	Empirical data from Florianopolis, Brazil

Table 2
Direct luminous efficacy models using independent variables other than solar altitude.

Model, 1st author (year)	Sky type	Light type	Input parameters	Data location
Perez et al. (1990)	All	Global Diffuse Direct	w, z, Δ^{a}	Empirical data from 10 American and three European locations
Molineaux et al. (1995)	All	Direct	m, β, w	Empirical data from Albany, US & Geneva, Switzerland
Muneer (1997)	All	Global Diffuse	ε	Empirical data from five locations in UK
Ruiz et al. (2001)	All	Global Diffuse	α ε	Empirical data from Madrid, Spain
Robledo and Soler (2001a)	All	Direct	α, Δ	Empirical data from Madrid, Spain
Robledo and Soler (2001b)	Intermediate Clear Overcast	Diffuse	Δ α, Δ	Empirical data from Madrid, Spain Empirical data from Madrid, Spain
De Souza et al. (2005)	All	Direct	α, Δ	Empirical data from Florianopolis, Brazil

ε: Clearness index, Δ: brightness index, w: atmospheric precipitable water content, z: solar zenith angle, α: solar altitude, m: optical air mass, β: turbidity factor.

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

3. The proposed model of luminous efficacy

3.1. Aims and advantages

The current work seeks to develop validated universal models for the direct 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

A number of websites offer satellite derived radiation and illuminance data for a limited number of locations. Data from two sites were used to develop the present models, the first being *Satel-light*, the European database of daylight and solar radiation (Satel-light, 2009). The website provides irradiance and illuminance data in different forms, including monthly means of hourly values. Data is available for the three main radiation types: global, direct and diffused incident for any defined surface orientation. Its geographic spread covers Europe and parts of North Africa and includes data for the period 1996–2000. Satel-light is used in this work to provide irradiance and illuminance monthly means of hourly values, from which luminous efficacy for the selected locations is directly calculated.

The second source is NASA Surface meteorology and Solar Energy (SSE) NASA, 2009. Data is available for the entire globe at a resolution of 1° in latitude and 1° in longitude, as monthly means for the years 1983–2005. SSE is used in this work to obtain data of independent variables such as hourly solar altitudes and cloud amount ratios. The solar altitude data is available as monthly averaged hourly solar angles, but cloud amounts are as monthly averaged three hourly values. From this, hourly values of cloud amounts are derived as follows. For instance, if cloud amount at 1200 and 1500 is *C12* and *C15*, respectively, cloud amount at 1300 and 1400 are calculated as ($0.67\ C12 + 0.33\ C15$) and ($0.33\ C12 + 0.67\ C15$), respectively.

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 10 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

A number of methods of investigating the accuracy of the various promulgated models are described in the literature and for consistency they will be used here. The statistical techniques used include mean bias deviations (MBD), root mean square deviations (RMS) and mean of absolute deviations (MAD). They are defined by the following equations:

$$\mathrm{MBD} = \sum_{i=1}^{N} (y_i - x_i)/N \tag{2}$$

$$\mathrm{RMS} = \left[\sum_{i=1}^{N} (y_i - x_i)/N \right]^{1/2} \tag{3}$$

Table 3
Locations frequencies of sky conditions and luminous efficacy.

City	Country	Location conditions			Sky conditions (%)			K_b (l m/W)		
		Lat (°N)	Lon (°E)	Alt (m)	Sun	Intermed.	Overcast	Max.	Min.	Mean
Copenhagen	DK	56	13	0	34	38	28	109	50	96
Moscow	RU	56	38	155	35	40	25	110	50	94
London	UK	51	0	15	31	42	27	110	50	98
Kiev	UA	50	31	169	38	35	27	110	50	99
Bordeaux	FR	45	1	9	47	34	19	110	50	100
Bucharest	RO	44	26	84	49	31	20	110	33	100
Valencia	ES	39	0	11	70	20	10	110	50	100
Athena	GR	38	24	110	68	21	11	110	50	102
Nador	MA	35	03W	155	67	24	9	109	50	102
Khania	GR	36	24	1	69	19	12	109	67	103

$$\mathrm{MAD} = \sum_{i=1}^{N} |y_i - x_i|/N \tag{4}$$

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.

4. Development of the proposed model

4.1. Luminous efficacy generation

Direct horizontal illuminance and irradiance data was obtained from Satel-light in the form of monthly means of hourly values for 10 ‘originating’ locations. From each the direct horizontal ‘reference’ luminous efficacy’ K_b, was 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°. It is clear that there are very similar maximum and minimum values and that the mean values gradually increases from around 95 for sites in northern locations to 103 for those further south. The average of the maximum, minimum and mean reference values are 110 lm/W, 50 lm/W and 99.4 lm/W, respectively.

4.2. Models developed from solar altitude

Polynomial and logarithmic functions for K_b against solar altitude, α, were obtained by plotting the variation of K_b with α for all 10 originating locations. Fig. 1 shows the best fit polynomial and logarithmic curves, which are as follows:

$$K_{b1} = -2E - 06\alpha^4 + 0.0006\alpha^3 - 0.0672\alpha^2 + 3.0984\alpha + 54.942 \tag{5}$$

$$K_{b2} = 13.871\ln(\alpha) + 53.348, \quad \text{if } \alpha > 1^\circ \tag{6}$$

In Eq. (6), to avoid the drop of calculated luminous efficacy under the lower threshold, values corresponding to solar latitude $\alpha \leqslant 1^\circ$ are assumed to be equal to the minimum K_b of 50 lm/W.

The relation between K_b and α^{-1} has been plotted in Fig. 2. The best fit curve is represented by the following polynomial function:

$$K_{b3} = 775.25\alpha^{-2} - 424\alpha^{-1} + 115.6, \quad \text{if } \alpha^{-1} > 0.3 \tag{7}$$

In Eq. (7) the mean minimum luminous efficacy for values corresponding to $\alpha^{-1} > 03$ (applicable to $\alpha \leqslant 1^\circ$) are assumed to be the minimum of 50 lm/W.

The relationship between K and sine α is plotted in Fig. 3 and the best fit curve is expressed in Eq. (8).

$$K_{b4} = 73.85(\sin\alpha)^3 - 193.5(\sin\alpha)^2 + 174(\sin\alpha) + 55 \tag{8}$$

4.3. Model developed from solar altitude and cloud amount

4.3.1. Alternative I

There is a direct relation between the cloud amount (C) and the amount of direct illuminance reaching the earth’s surface. To investigate the relationship between the cloud amount C, solar altitude α, and luminous efficacy; values of α multiplied by $(1 - C)$ are been plotted against K_b (see Fig. 4). Inspection of Figs. 1 and 4 show that the variation of K_b with α is less scattered when α is adjusted by $(1 - C)$.

It can also be seen in Fig. 4 that for values of $\alpha(1 - C)$ greater than approximately 2000, the relationship becomes almost linear and horizontal. The slope of the polynomial curve rises and falls according to its degree, while the logarithmic curve continues to rise (see Fig. 4). Therefore, two split curves are proposed to represent the relationship; polynomial or logarithmic curves if $\alpha(1 - C) \leqslant 2000$, and a linear curve if $\alpha(1 - C) > 2000$. The best fit curves, shown in Fig. 5, are obtained as follows:

$$K_{b5} \quad \text{if } \alpha(1 - C) \leqslant 2000 = -2E - 05[\alpha(1 - C)]^2 + 0.062\alpha(1 - C) + 61.62, \quad \text{Otherwise} = 0.0009\alpha(1 - C) + 104.6 \tag{9}$$

$$K_{b6} \quad \text{if } 50 \leqslant \alpha(1 - C) \leqslant 2000 = 16.24\ln[\alpha(1 - C)] - 12.126, \quad \text{otherwise} = 0.0009\alpha(1 - C) + 104.6 \tag{10}$$

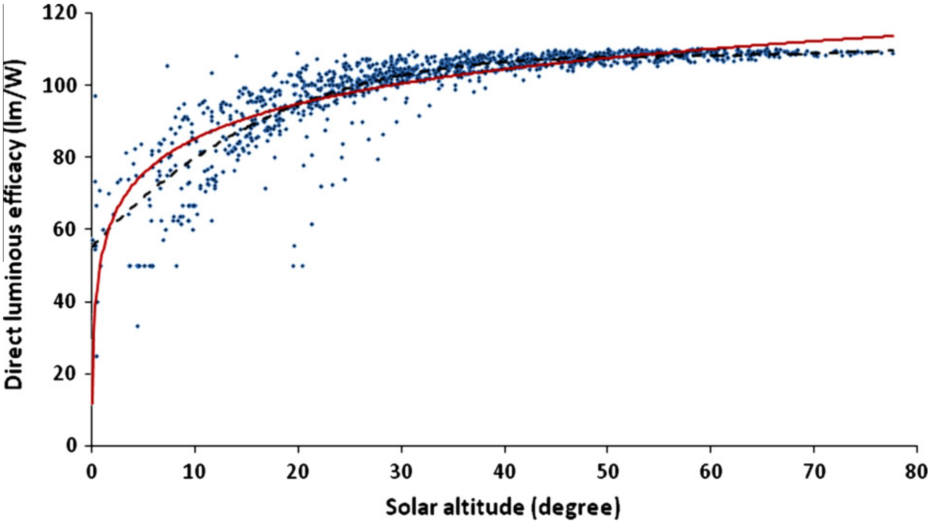

Fig. 1. Direct luminous efficacy plotted against solar altitude.

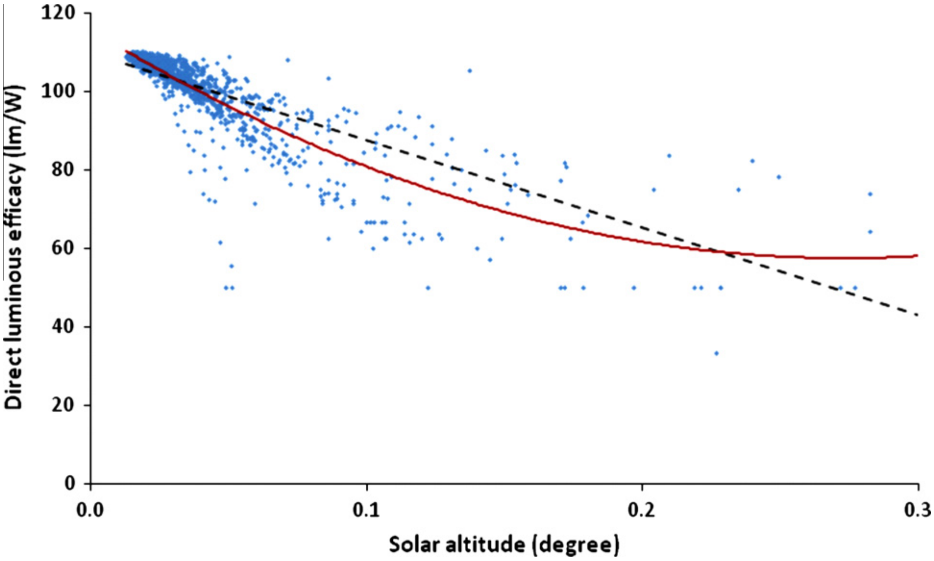

Fig. 2. Direct luminous efficacy plotted against 1/solar altitude (α^{-1}).

In Eq. (10), the mean minimum luminous efficacy for values corresponding to $\alpha(1-C) \leqslant 50$ (applicable to $\alpha \leqslant 1°$) are assumed to be the minimum of 50 lm/W.

4.3.2. Alternative II

To further refine the model, cloud amount was investigated as a weighting parameter. In Fig. 6, the values obtained for α/C was plotted against K_b for the 10 originating locations giving an almost linear relationship. The best fit linear and polynomial curve were as follows:

$$K_{b7} = -4.2(C/\alpha) + 110.9 \tag{11}$$

$$K_{b8} = -0.004(C/\alpha)^4 + 0.136(C/\alpha)^3 - 1.28(C/\alpha)^2 - 1.21(C/\alpha) + 109.76 \tag{12}$$

In Eqs. 11 and 12, the lower threshold of luminous efficacy for values corresponding to $(C/\alpha) \geqslant 12$ (applicable to $\alpha \leqslant 1°$) are assumed to be equal to the minimum K_b of 50 lm/W.

5. Validation of the proposed models

The proposed models have been used to generate illuminance values for the 10 ‘originating locations’. The generated values were compared with the actual values for the corresponding location. In addition four more cities, not used to develop the models, 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

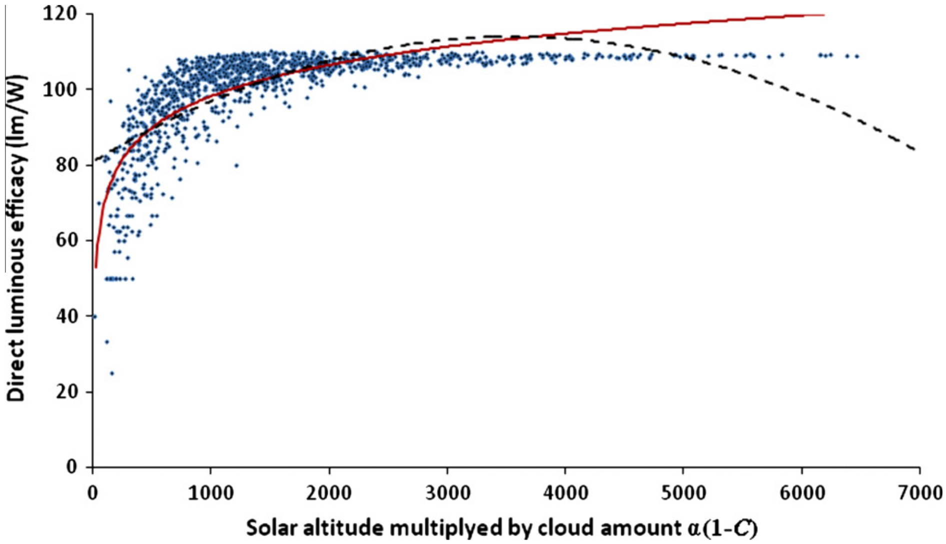

Fig. 3. Direct luminous efficacy plotted against solar altitude and cloud amount ($\alpha(1-C)$).

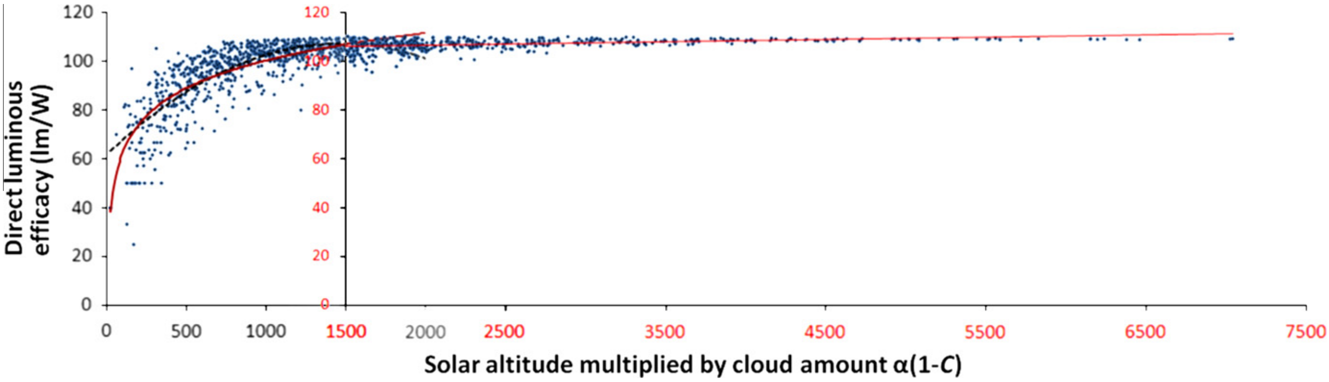

Fig. 4. The split curves represent direct luminous efficacy plotted against solar altitude and cloud amount ($\alpha(1-C)$).

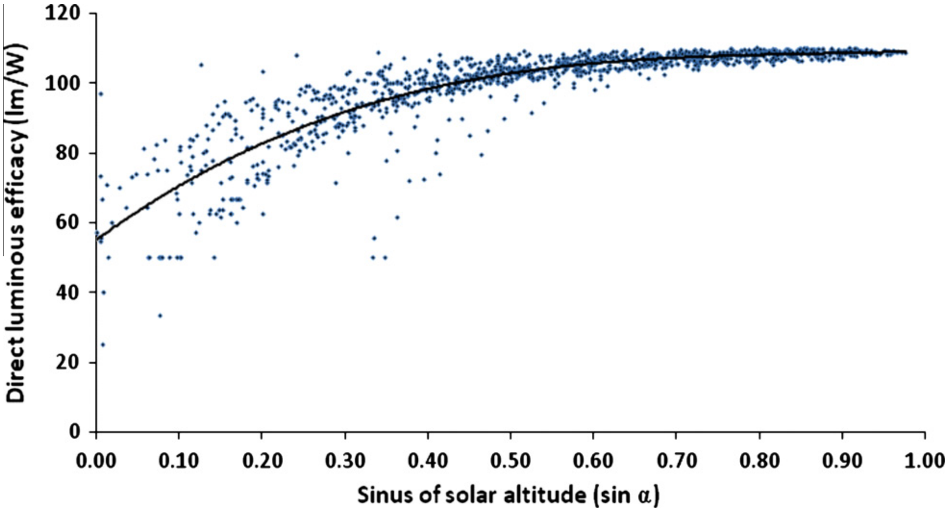

Fig. 5. Direct luminous efficacy plotted against sine of solar altitude.

5.1. Statistical performance of the models developed from solar altitude

Fig. 7 shows the statistical performance of the models described by Eqs. (5)–(8), named *M-1.1, M-1.2, M-1.3* and *M-1.4*, respectively. It can be seen from Fig. 7 that, for either originating or validation locations, that the models developed using solar altitude α, have the following statistical performance ranges: MAD = 0.2 : 1.5%, RMS = 0.3:2.4% and MBD = 0:−2%. The use of α^{-1} (Eq. (7)) or sin α (Eq. (8)) improves the model performance markedly

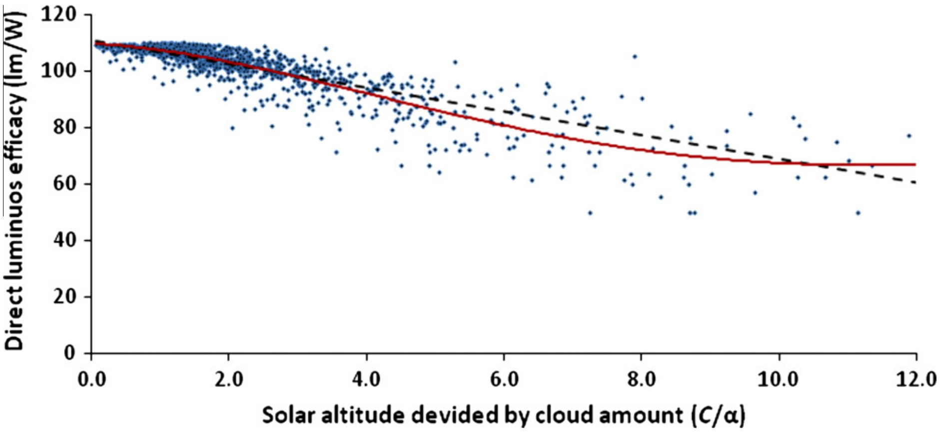

Fig. 6. Direct luminous efficacy plotted against solar altitude and cloud amount (C/α).

with the statistical indicators showing upper thresholds of 0.6%, 0.8% and −0.3%, respectively. The MBD indicator shows that all four models give underestimations although the statistical indicators of performance for the northern locations are generally better than those further south.

Fig. 8 shows the estimated efficacy values calculated using the four models. The variations between the average reference maximum value and the average maximum values estimated using *M-1.1*, *M-1.2*, *M-1.3* and *M-1.4* are −5, 2, −0.3 and −1 lm/W, respectively (see Table 4). For the corresponding mean values, the differences are −2.4, −0.7, −1.1 and −0.8 lm/W. This suggests that *M-1.3* and *M-1.4* offer the most accurate representation in terms of maximum and mean values.

5.2. Statistical performance of the models developed from solar altitude and cloud amount

Fig. 9 shows the statistical performance of the models described by Eqs. 9 and 12, namely *M-2.1*, *M-2.2*, *M-2.3* and *M-2.4*. It can be seen from Table 4 that the first three models give very similar results with *M-2.4* performing best. The results suggest that the use of the cloud amount factor as a weighting parameter does not lead to major improvements compared with those calculated using solar altitude only. The statistical performance ranges between MAD = 0.2:0.8%, RMS = 0.3:1.1% and MBD = −0.8:0.5%.

There is no evidence that there is any systematic variation in the results of the statistical performance indicators between the northern and southern locations. This suggests that the models are robust for all latitudes investigated.

Fig. 10 shows the efficacy values for the four models. Comparison between the average reference and estimated efficacy values show that the differences between the maximum values for *M-2.1* and *M-2.2* are negligible at 0.3 and 0.6 lm/W, respectively but are over 2 for both of *M-2.3* and *M-2.4*. The insignificant differences between the mean values for the four models, ranging from −0.5 and 0.6, suggest that all could used for estimation purposes.

6. Published 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. 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.

6.1. Horizontal direct luminous efficacy models

The models considered for estimation of the direct luminous efficacy on horizontal surface were:

6.1.1. Aydinli and Krochmann (1983)

This is often referred to as a pioneering model based on spectral data. The relation between K_b and α is represented by the following polynomial function:

$$K_{b8} = -8.41 \times 10^{-10}\alpha^{-5} - 2.17 \times 10^{-6}\alpha^{4} + 0.00074\alpha^{3} - 0.0876\alpha^{2} + 4.459\alpha + 17.72 \tag{13}$$

6.1.2. Molineaux et al. (1995)

This used the parameters of relative optical air mass (hereafter simply called air mass, m), atmospheric turbidity and water vapour content to develop three models. The model is based on the air mass expressed in the form of exponential function:

$$K_{b9} = 119\exp(-0.1\mathrm{m}) \tag{14}$$

6.1.3. Robledo and Soler (2001a)

This model was developed using the brightness index, Δ, as an attenuation factor. The model was expressed in many forms; the simplest one is as following:

$$K_{b10} = 134.27(\sin\alpha)^{0.269}e^{-0.0045\alpha}(1.045 - 0.427\Delta) \tag{15}$$

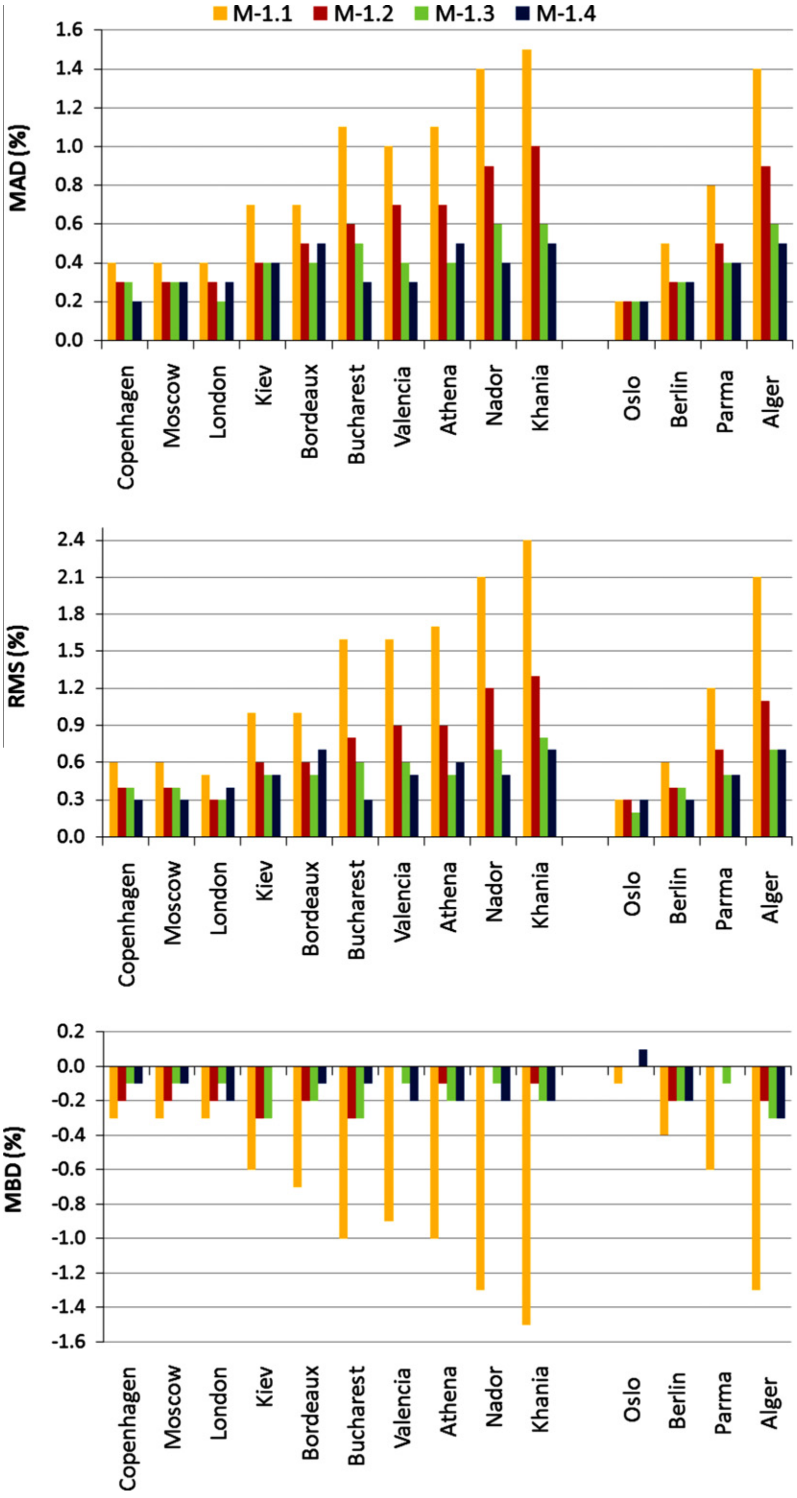

Fig. 7. Statistical assessment of models developed based on solar altitude.

6.2. Statistical assessment

The models given by Eqs. (13)–(15) were used to estimate direct illuminance values on horizontal surface for the 10 originating locations and Table 4 reports the average statistical performance of the estimated values. The MAD and RMS ranged from 1.69%:2.72% and 1.89%:3.46%, respectively. The predicted value is underestimated by between 1.67% and 2.71%.

The difference between the average estimated maximum and reference efficacy is within the range 6–13 with the difference between the mean values being between 10.3 and 14.9. On this evidence the model developed by Molineaux appears to be the best of the published models investigated.

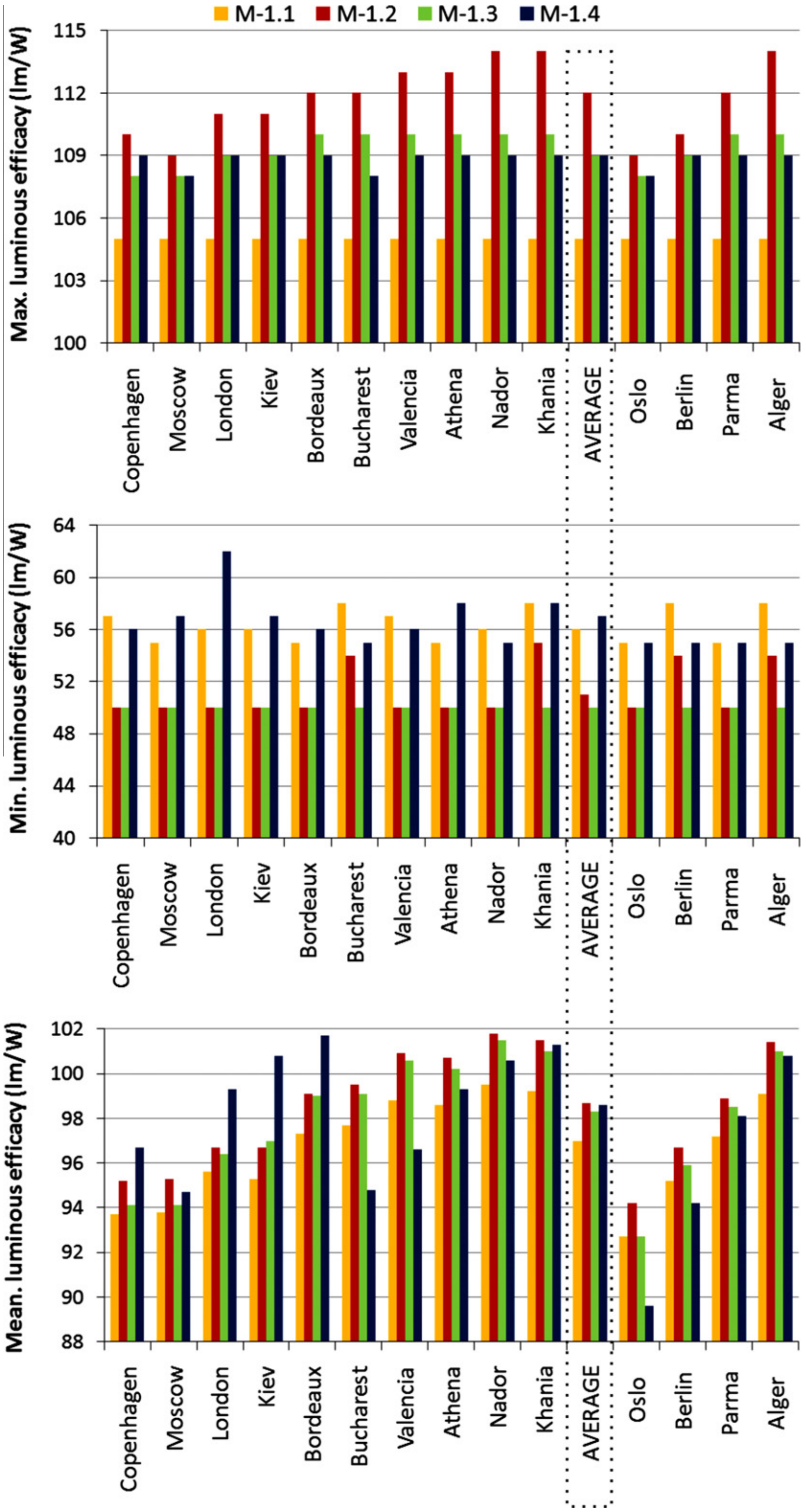

Fig. 8. Estimated luminous efficacy values (l m/W) from models based on solar altitude.

7. Comparison of models

It is clear that no one of the proposed models performs best over all the 14 locations. However that with the best overall performance can be selected by reference to the statistical indicators and the average difference between the luminous efficacy values of the reference values and those generated by the models. These may also be compared with the performance of the best published models.

Inspection of the statistical indicators and K_b differences in Table 4 suggests that model *M-1.1*, a polynomial function for K_b against α, can be rapidly dismissed. Of the remaining models the best performers emerge as *M-1.3,*

Table 4
Average statistical performance for all models.

Models		MAD (%)	RMS (%)	MBD (%)	K_b differences		
					Max.	Min.	Mean
M-1.1	[Eq. (5)]	0.87	1.31	−0.79	−5	6	−2.4
M-1.2	[Eq. (6)]	0.57	0.74	−0.16	2	1	−0.7
M-1.3	[Eq. (7)]	0.41	0.53	−0.17	**−0.3**	**0**	−1.1
M-1.4	[Eq. (8)]	**0.37**	**0.48**	**−0.14**	−1	7	0.8
M-2.1	[Eq. (9)]	0.54	0.68	0.06	**0.3**	14	0.8
M-2.2	[Eq. (10)]	0.58	0.72	−0.13	1	2	**−0.3**
M-2.3	[Eq. (11)]	0.50	0.60	−0.21	−2	**0**	**−0.3**
M-2.4	[Eq. (12)]	0.43	0.54	−0.14	−2	**0**	−0.5
Aydinli	[Eq. (13)]	2.41	2.68	−2.41	9	29	14.9
Molineaux	[Eq. (14)]	1.69	1.89	−1.67	6	43	10.3
Robledo	[Eq. (15)]	2.72	3.46	−2.71	13	17	10.4

M-1.4 and *M-2.4*. These are, respectively, polynomial functions for K_b against α^{-1}, K_b against sin α and K_b against C/α. Their statistical indicators for average MAD, RMS and MBD for *M-1.3* are $0.41\% \pm 0.2$, $0.53\% \pm 0.25$ and $-0.17\% \pm 0.1$, respectively; for *M-1.4* are $0.37\% \pm 0.15$, $0.48\% \pm 0.2$ and $-0.14\% \pm 0.1$; and for *M-2.4* are $0.43\% \pm 0.2$, $0.54\% \pm 0.2$ and $-0.14\% \pm 0.35$. In terms of maximum average difference in luminous efficacy values their respective values are −0.3, −1 and −2. The mean values have variation of −1.1 for *M-1.3*, −0.8 for *M-1.4* and −0.5 for *M-2.4*. Taking the statistical indicators and K_b differences together these models emerge as best. They are some five times better, according to the statistical indicators, than the best published model (see Fig. 11).

Fig. 12 displays the maximum, minimum and mean differences between average luminous efficacy values estimated by the models and the reference values. The differences for *M-1.3*, *M-1.4* and *M-2.4* of between zero and 1.6 lm/W for maximum, minimum and mean are clearly superior to the published models. Of these Molineaux's model performs best in terms of the maximum and means, and Robeldo's for minimum. However the magnitudes of the differences are high – for example mean values vary by some 5–10 lm/W from those of the reference values.

8. 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 gathered during International Daylight Measurement Year from the following locations (IDMP-CIE, 0000):

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

The proposed models that included cloud amount (described in Section 4.3) could not be tested since the measured data did not include simultaneous cloud amounts.

The average statistical performance of all the models is shown in Table 5 shows that the best performance for any given location is for one of the proposed models. The average performance figures show very similar results for *M-1.2, M-1.3* and *M-1.4* in terms of MAD and RMS. All are better than *M-1.1.* The MBD indicator suggests that *M-1.2* and *M-1.4* produce estimated average illuminance values almost identical to the measured ones. Therefore comparison with measured data confirms that *M-1.4* can be considered to be the best proposed model. Among the published models that of Molineaux gives the best average performance but in comparison with *M-1.4*, its statistical indicators for average MAD, RMS and MBD are 0.53%, 0.58% and 1.6% higher.

Fig. 13 also illustrates the relationship between the best performing models (*M-1.1* and *M-1.4)* and the published models for locations having different latitudes. It is clear that judged on all the statistical indicators the proposed models produce results some 1.5 times better than using the published methods.

It should be noted that all of the models are progressively less accurate for more southern locations but those based on solar altitude and cloud amount exhibit less such variability. Thus the use of model *M-1.4* in Northern locations (above 40 Latitude) or where no cloud data is available is advocated, and that of *M-2.4* in more southern locations. Input data for the models is monthly averaged hourly solar angles for the site and/or cloud amounts as monthly averaged hourly values as described in Section 3.2.

9. Conclusion

The general dearth of measured daylight data suitable for lighting design purposes presents a barrier to the wider use of this resource. Measured daylight data is available for locations in North America, Japan and Europe, although not enough to provide full coverage. There are many parts of the world – indeed whole continents – where comprehensive daylight data is not available at all.

Irradiance data is much more widely available and a number of techniques have been published to enable this

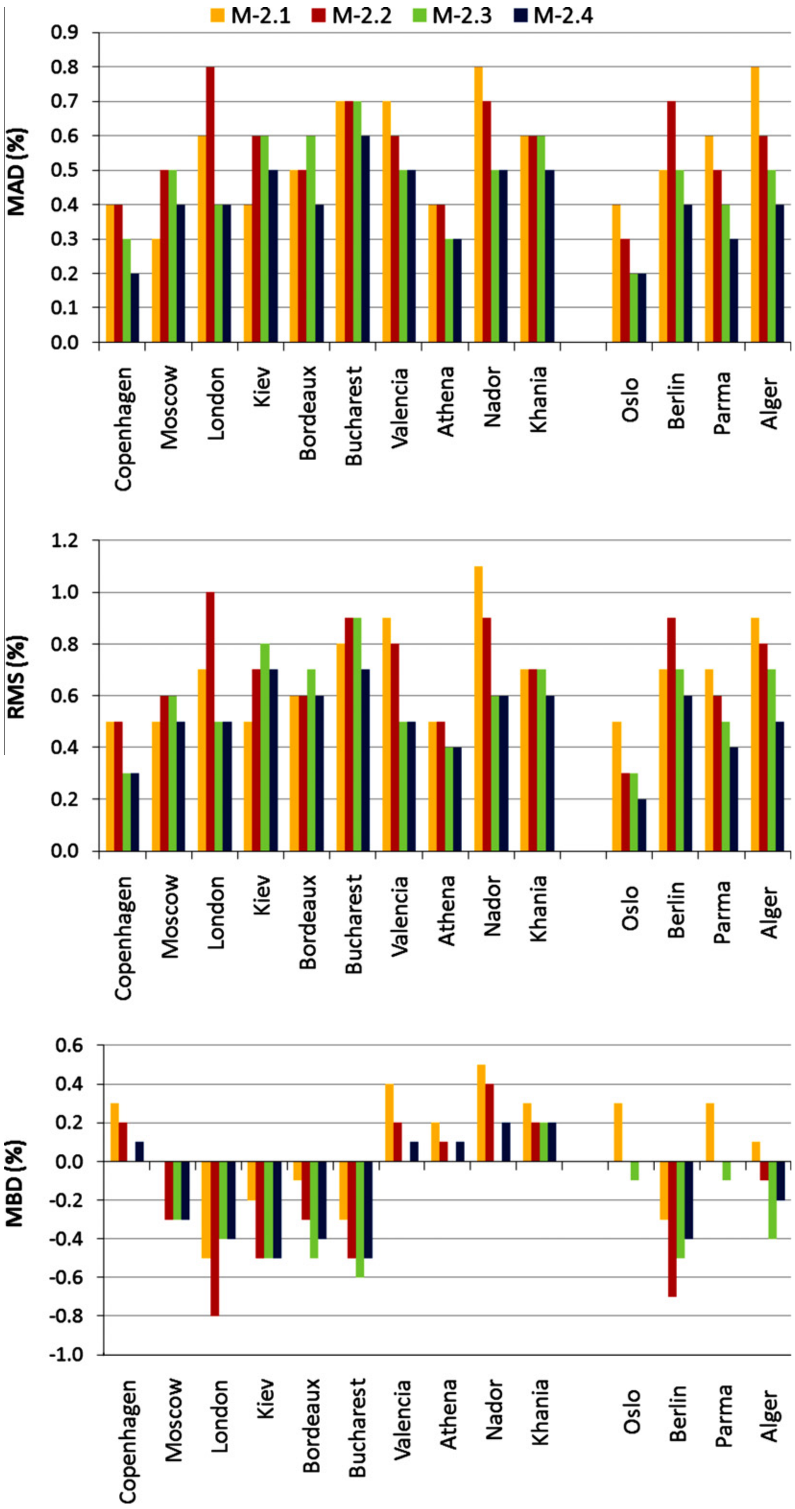

Fig. 9. Statistical assessment of models based on solar altitude and cloud amount.

to be converted to useful illuminance data using the concept of luminous efficacy. The promulgated models are based variously on the relation between luminous efficacy and solar altitude and/or cloud amount and some require more extensive data to calculate local coefficients. This is a limiting factor in their wider applicability.

This work presents a new method of estimation of horizontal direct luminous efficacy based on satellite data which is widely available, free of charge, on web servers. The resulting models are universal with a minimum requirement for additional variables or coefficients. It makes the availability of realistic design illuminance data

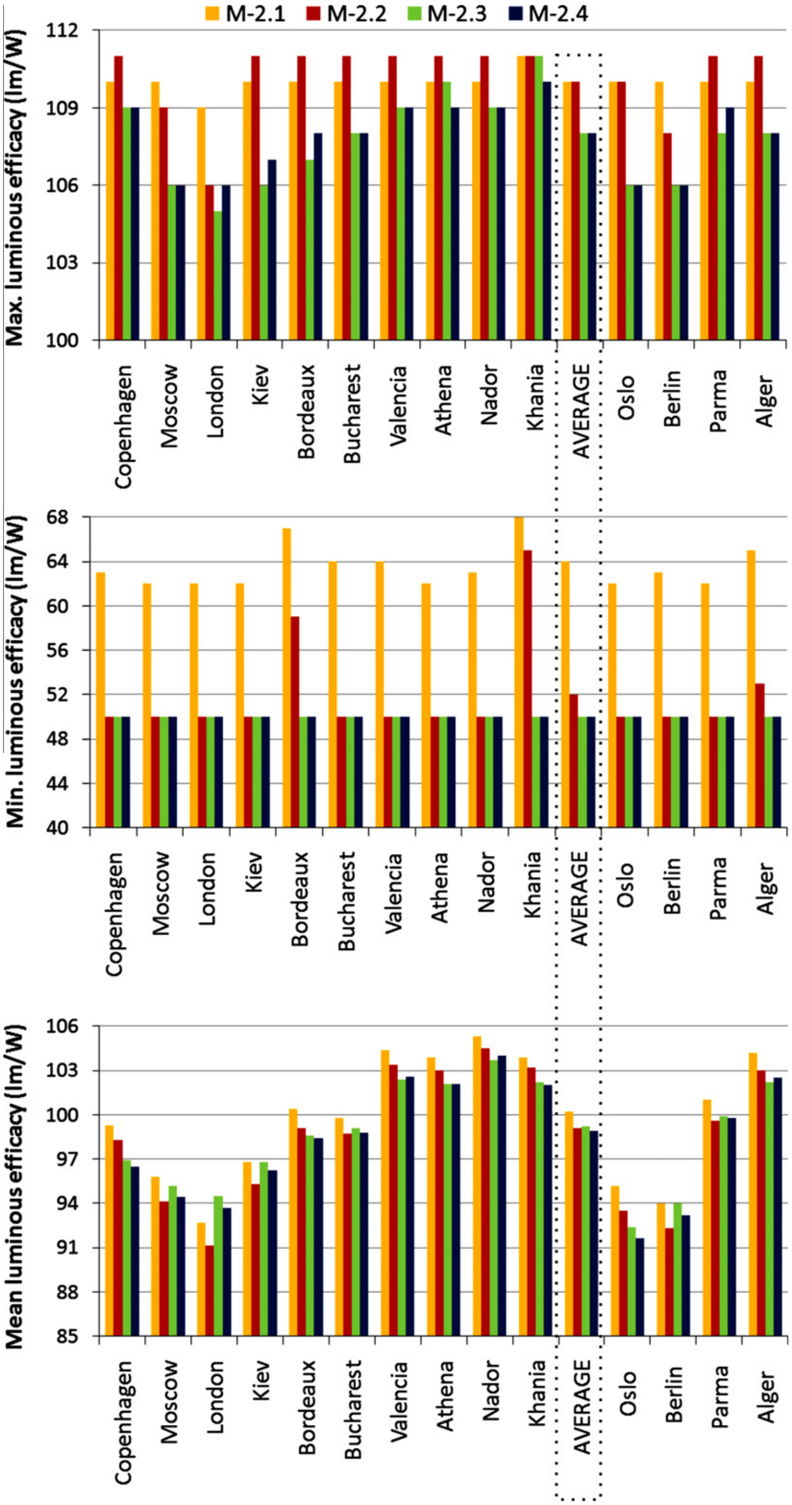

Fig. 10. Estimated luminous efficacy values (l m/W) from models based on solar altitude and cloud amount.

independent of the availability of local measured daylight data. For these reasons the satellite based approach to generation of illuminance data is likely to become increasingly important for design purposes.

The new approach was developed using satellite irradiance and illuminance data for 10 locations in Europe and North Africa. The proposed models were developed from the relation between the luminous efficacy and solar altitude/cloud amount. The methods presented here produce more accurate estimates of luminous efficacy than existing published models, but without the use of extensive local data. The work suggests that the method can be applied

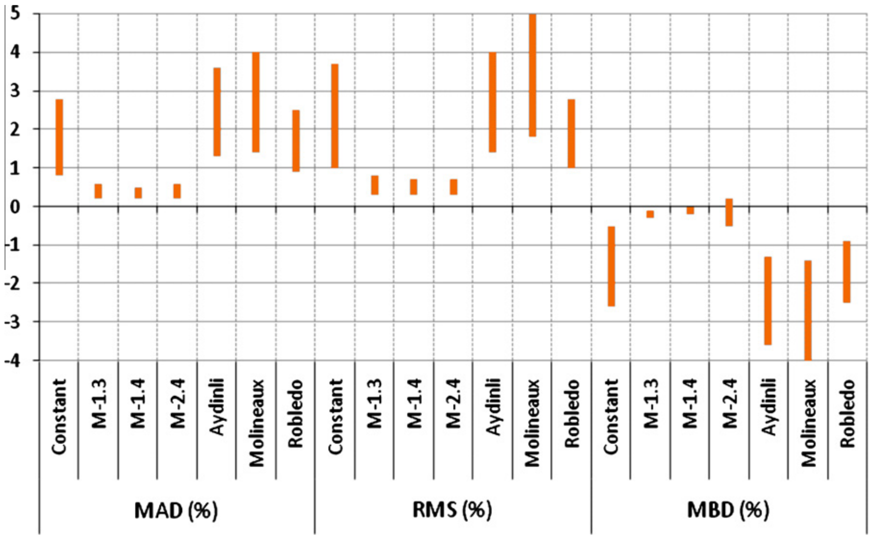

Fig. 11. Ranges of MBD, RMS and MAD values between the estimated and given direct luminous efficacy.

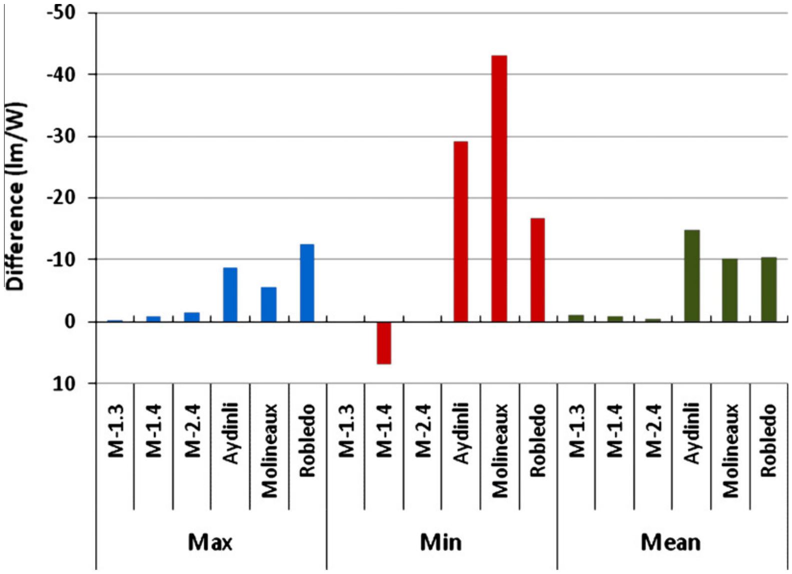

Fig. 12. Maximum, minimum and mean differences between the estimated and given average direct luminous efficacy values.

to a wide range of geographical locations. Satellite irradiance data is available for all points on earth's surface so, in principle, luminous efficacy can be estimated for all locations.

Direct horizontal illuminance monthly means of hourly values were estimated using the models. A statistical assessment of estimated and actual values showed that models *M-1.4* and *M-2.4*, expressed by Eqs. 8 and 12, give the best performance over the 14 locations throughout Europe and North Africa. The same statistical assessment tools were applied to compare the best proposed and published models. The comparison showed that use of models *M-1.4* and *M-2.4* gave efficacy values with low statistical errors over a wide range of locations, regardless their characteristic sky conditions and up to five times more accurate than published methods. In the final part of the work, the published and proposed models were used to estimate illuminance data for four locations for which actual irradiance and solar altitude data was available. The statistical indicators showed that *M-1.4* was some 1.5 times more accurate than using the published models.

All of the models were progressively less accurate for more southern locations but those based on solar altitude and cloud amount exhibited less such variability. Thus the use of model *M-1.4* in Northern locations (above 40 Latitude) or where no cloud data is available is advocated, and that of *M-2.4* in more southern locations. Input data for the models is monthly averaged hourly solar angles for the site and/or cloud amounts as monthly averaged

Table 5
Average statistical performance of proposed and published models.

Models	Edinburgh			Bratislava			Arcavacata			Fukuoka			Average		
	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)	MAD (%)	RMS (%)	MBD (%)
M-1.1	**1.4**	**2.4**	**0.0**	**1.7**	2.3	**0.2**	**2.5**	**3.8**	−0.9	3.5	5.8	−3.1	2.28	3.58	−0.95
M-1.2	**1.4**	2.5	0.2	**1.7**	**2.2**	0.8	3.0	4.5	0.6	**2.6**	**4.1**	−**2.1**	2.18	3.33	−**0.13**
M-1.3	**1.4**	2.5	0.2	**1.7**	**2.2**	0.8	2.7	4.1	**0.4**	2.7	4.3	2.3	2.13	**3.28**	0.93
M-1.4	**1.4**	2.5	0.2	**1.7**	**2.2**	0.9	2.6	4.0	**0.4**	2.7	4.4	−2.3	**2.10**	**3.28**	−0.20
Aydinli	1.8	2.8	−0.9	2.2	3.0	−1.8	3.9	5.2	−3.3	4.5	6.8	−4.4	3.10	4.45	−2.60
Robledo	1.8	3.0	−1.3	2.6	3.6	−2.0	4.1	5.6	−3.7	5.0	7.8	−4.9	3.38	5.00	−2.98
Molinx	1.6	2.6	−0.6	1.8	2.4	−0.9	3.2	4.4	−2.0	3.9	6.0	−3.7	2.63	3.85	−1.80

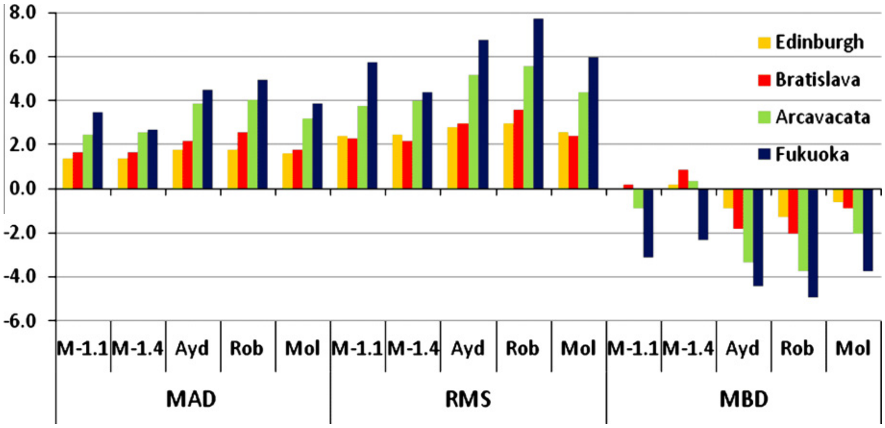

Fig. 13. The relationship between the models statistical performance and the location longitude.

hourly values, all of which are available for the websites cited in this work.

This work has its origins in study of daylight guidance systems but could equally be applied to other lighting technologies. The results suggest that the different methods of estimating luminous efficacy show substantial differences. Those between some of the models and the reference data are of the order of 10–15 lm/W. This is a significant difference when converted to illuminance. This has implications for sizing of devices such as roof-lights or guidance systems, which in turn may influence their performance in use and economic viability. Importantly the techniques described here permit accurate estimation of direct luminous efficacy, and hence daylight amounts, for all locations for which satellite irradiance data is available. This makes daylight data available to designers at locations remote from current measurement sites.

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