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A model to estimate direct luminous efficacy based on satellite data

M.S. Mayhoub [1], D.J. Carter *

School of Architecture, University of Liverpool, Liverpool L69 3BX, UK

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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

* Corresponding author. Tel.: +44 (0) 151 794 2622.
E-mail address: eb09@liverpool.ac.uk (D.J. Carter).
[1] Al-Azhar University, Cairo, Egypt.

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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