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Estimation of the daylight amount and the energy demand for lighting for the early design stages: Definition of a set of mathematical models

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ABSTRACT

A set of logistic mathematical models to estimate the daylight amount and the energy demand for lighting of a room is presented. The models were built upon a database of results obtained for a sample room through Daysim simulations: features such as site, orientation, external obstructing angle, window size, glazing visible transmittance and room depth were parametrically changed, resulting in 102 cases. For each case, the target workplane illuminance and the lighting power density were also changed, producing a final database of 408 cases. Two groups of models were built, for two different external obstructions: a building ahead and an overhang used as shading system. Each group contains a set of models for different daylighting metrics (daylight autonomy, continuous daylight autonomy and spatial daylight autonomy) and for the energy demand for lighting, considering a manual on/off switch or automated daylight responsive lighting control. The estimates that were obtained using the models showed, compared to the corresponding simulations results, a coefficient of variation CV lower than 16% for all the models, with one exception, having a CV up to 30%.

The aim of the study was to elaborate models that could be used to incorporate daylighting strategies since the earliest stages of the building design process. Using the models, it is possible to predict the annual daylight amount in a room and the corresponding energy consumption of the lighting systems starting from some given room features (for instance the room depth or the window area) or, the other way around, estimate the suitable values of room features (glazing area, visible transmittance or room depth) to guarantee a target value of energy demand for lighting or of a daylighting metric.

1. Introduction

Daylighting is largely acknowledged to be one of the key factors in the design of low/zero carbon emission buildings. Furthermore, it is not only a cost effective alternative to electric lighting, but also contributes to create more stimulating, comfortable and healthy indoor environment for the occupants. Consistently, several studies have been performed on the role played by daylighting within the design process for both the indoor environmental quality and the energy performance of a building. In this context, the so-called climate-based daylighting modeling (CBDM) was introduced to more accurately quantify the daylighting inside a building space, accounting for the specific climate, in terms of dynamic variation of sunlight and daylight availability of the considered building site [1].

In spite of its acknowledged importance, daylighting design is rarely implemented into a project since the earliest design stages onward [2–5]. The development of an architectural project for a building is more likely based on formal or aesthetical or technological principles rather than on daylighting or energy based strategies. This tendency may be due to a number of concurring factors. On the one hand, the impact of daylighting on the Indoor Environmental Quality (IEQ) and on the total energy demand for a building is a complex phenomenon to handle at the beginning of the conceptual phase [6]: simulation tools are needed, that require lengthy input process and are too time consuming to use for most architects and designers. On the other hand, there is a lack of metrics which allow this phenomenon to be addressed in a synergic way. Focusing particularly on daylighting aspects, the new metrics derived from the CBDM [7,8] are difficult to be fully managed by non-expert users and need advanced simulation tools to be accurately calculated. As a result, daylighting strategies, when addressed, are based on experience or on the use of empirical methods associated with rules of thumbs [9].

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A key factor is the lack of simple and quick evaluation tools to be used at the beginning of the design process to get information on the suitability of daylighting and its potential to save energy. Some attempts to bridge this gap can be found in the literature, through the development of simplified predictive tools for the earlier design stages. Krarti et al. [10] developed a simplified mathematical model to evaluate the potential of daylighting to reduce the energy consumption for electric lighting in office buildings. The study was based on a parametric analysis where several combinations of building geometry, window size, and glazing type for four geographical locations in the United States were modeled and simulated using DOE 2.1E. The mathematical model estimates the percent savings in the annual use of electric lighting, due to the exploitation of daylighting through dimming controls, as a function of window glazing transmittance, window area to perimeter floor area. In a later study [11], the model was refined and further developed to include several US and international locations, assessing the effect of both continuous dimming and stepped daylighting controls.

Using different approaches, Moret et al. [12] developed a simple mathematical model to predict the impact of electric lighting and fenestration controls on the total energy savings (lighting, heating and cooling) in commercial buildings, while Fonseca et al. [13] and Wong et al. [14] used multivariate non-linear regression techniques via an artificial neural network ANN. The model developed by Fonseca et al. [13] allows predicting the impact of daylighting on the final energy requirement for a building and was based on the results of Daysim and Energy Plus simulations of a building located in Florianopolis, Brazil. The model developed by Wong et al. [14] allows estimating the daily total energy demand for a building (energy demand for lighting, cooling and heating) and was created based on the results of Energy Plus simulations of a building located in Hong Kong.

A different approach, with different goals, was adopted in two complementary studies, which are based on the same database of simulations results, by Cammarano et al. [15] and Pellegrino et al. [16]. Cammarano et al. developed a simple graphical tool to assess indoor daylighting and to determine which combinations of architectural features are able to provide high, acceptable or low daylight levels within a room. Pellegrino et al. analyzed the impact of the daylight amount, due to different architectural and lighting control features of a building on the energy demand for lighting, cooling and heating.

The approaches adopted in the above studies, as well as the variables included and the output that was obtained, are summarized in Table 1.

It appears that above studies were predominantly focused on the energy aspects concerned with daylighting, allowing the energy demand for lighting (alone, or integrated with the energy demand for lighting and for cooling) to be predicted. In one case [10,11], the models allow the energy saving concerned with a number of lighting controls to be estimated, rather than the energy demand in absolute value. No mathematical models have been found for a quick calculation of the dynamic daylighting metrics derived from the CBDM [7,8], the study by Cammarano et al. [15] being quite an isolated case, but based on a graphical tool and referred to a limited set of variables.

Within this frame, this paper presents a set of mathematical models that were developed to estimate the impact that room variables, in terms of geometry, optical properties of materials, and characteristics of the lighting systems, have on both the daylighting and the electric lighting performance of a room. Potentially, the models are intended to be used in the earliest stages of the building design process, when the daylighting strategies are initially explored and defined.

Basically, the mathematical models were built from the results of a parametric study: a sample room was modeled and simulated using Daysim, modifying a number of its characteristics. As a result, a database of values of different climate-based daylighting metrics and of energy demand for lighting was obtained and then processed mathematically using multivariate non-linear regression techniques. In detail, the set of models contains equations to calculate metrics such as the Daylight Autonomy (DA), the continuous Daylight Autonomy (DA_{con}) and the spatial Daylight Autonomy ($sDA_{300,50\%}$), as well as to calculate the corresponding energy demand for lighting. The models allow estimating the value of daylighting metrics that have been recently implemented in regulations or protocols to assess the IEQ and energy performance of a building (the spatial Daylight Autonomy [8], included in the LEED-US [17]; the Daylight Autonomy, in the UK Priority School Building Programme [18]). Complementarily, the models also allow estimating the energy use as a consequence of daylighting and type of lighting systems, especially in the presence of a continuous dimming control system.

Compared to the other models available in the literature and mentioned earlier, the models proposed in this study allow a more thorough and extensive analysis to be carried out. On the one hand, the daylighting conditions in a room can be analyzed, through a large set of climate-based daylighting metrics, such as the group of Daylight Autonomies. On the other hand, the energy demand for lighting associated with the daylight amount in a space and its exploitation through the presence of some lighting control systems (such as a manual on/off switch or a photo-dimming responsive control) can be estimated as well. The models developed in the study included a large set of variables, in terms of architectural features of a building, larger than in previous studies, and with a broader range of values. Furthermore, the presence of two types of obstructions was introduced into the models: a building ahead of different height and an overhang of different depth.

The Authors developed an earlier mathematical model to estimate the energy demand for lighting, given geometrical, photometric and lighting system's characteristics of a room [19]. Therefore, the present study is also aimed at refining and expanding the previous model, to create a set of homogeneous predictive models to allow both the daylight amount and distribution and the corresponding energy demand for lighting to be estimated.

2. Methodology

The methodology adopted in this study is based on a series of statistical analyses, which were applied to the results of a set of simulations carried out to estimate the daylighting and the energy demand for lighting for a room whose characteristics were parametrically changed. Two groups of models were built:

a) one group of models is to calculate some daylighting metrics, which describe the daylight amount and distribution in a space. In detail, the models that were developed for the following metrics are presented in this paper: Daylight Autonomy, DA [7]; continuous Daylight Autonomy, DA_{con} [7]; spatial Daylight Autonomy, $sDA_{300,50\%}$ [8]
b) one group of models is to calculate the energy demand for lighting, ED_{room}, as integration between daylighting and electric lighting, for the considered room. Two models were developed, for the following control systems: manual on/off switch and continuous dimming, based on the daylight illuminance measured over the workplane.

Among the geometries that were changed for the simulated sample room, a particular interest was paid to the presence of an