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A multivariate non-linear regression model to predict the energy demand for lighting in rooms with different architectural features and lighting control systems

Valerio R.M. Lo Verso [a,*], Anna Pellegrino [a], Franco Pellerey [b]

[a] Politecnico di Torino, Department of Energy, TEBE Research Group, corso Duca degli Abruzzi 24, 10129 Turin, Italy
[b] Politecnico di Torino, Department of Mathematical Sciences, corso Duca degli Abruzzi 24, 10129 Turin, Italy

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ABSTRACT

The paper presents a set of logistic mathematical models to quickly estimate, since the earliest design stages, the electric lighting energy demand for a generic room with different architectural features (site, orientation, external obstructing angle, window size, glazing visible transmittance and room depth), lighting system characteristics or users' lighting requirements (working plane illuminance, lighting power density, type of lighting control). The models were built upon the data obtained from a parametric study, based on simulations carried out through Daysim of 828 case-studies. Two dataset were obtained: one for rooms with a manual on-off switch lighting control and one for rooms with an automatic daylight responsive lighting control. Consistently, two specific models were derived, one for each control system.

The average error of the mathematical models in estimating the lighting energy demand with respect to the results of Daysim simulations was quantified in terms of the normalized Mean Bias Error value (0.66% – for the manual control system model and 0.29% – for the automatic daylight responsive control system model) and of the Coefficient of Variation of the Root Mean Squared Error (3.45% and 5.34% for the two models, respectively).

1. Potential referees

- **Marilyne Andersen**, associate professor, Ecole Polytechnique Fédérale de Lausanne EPFL (Swiss Federal Institute of Technology Lausanne), School of Architecture, Civil and Environmental Engineering ENAC, Bâtiment BP, Station 16, Office BP2229, Route Cantonale, CH-1015 Lausanne, phone: +41 21 69 30882 (or 30883), marilyne.andersen@epfl.ch
- **Jan De Boer**, Group Leader Lighting Technology/Department Heat Technology, Fraunhofer Institute of Building Physics, Nobelstrasse 12, D-70569 Stuttgart, phone: +49 711/970-3401, fax: +49 711/970 3399, jdb@ibp.fraunhofer.de
- **Massimo Paroncini**, full professor, Department of Energetics, Università Politecnica delle Marche, via Brecce Bianche–Monte Dago, 60131 Ancona, Italy, phone: +39 071 220 4762, fax: +39 071 220 4770, m.paroncini@univpm.it

2. Introduction

The issue of directives and legislations aimed at reducing the energy consumption and wastage in private and public buildings has noticeably changed the focus of the building design approach over the last decade. Attention to the global energy performance of buildings, that results from energy consumptions used for heating, cooling, lighting and hot sanitary water has increased as a consequence [1,2]. Accounting for all these energy-demand contributions plays a crucial role towards pursuing the goals set by the European Union to reduce the building energy consumption [3] and to promote the diffusion of Zero of Near-Zero Energy Buildings [4].

In the lighting sector, a key factor to substantially reduce the energy consumption of electric lighting is a more widespread exploitation of daylight, associated with the use of the most energy efficient lighting technologies, including electric lighting controls, in accordance with an increased and more conscious implementation of the building automation principles [5]. Nevertheless, in the fields of both architectural design and lighting design there is still a lack of objective information and data on the impact that different design solutions, in terms of both building architectural features influencing indoor daylight availability or lighting control

* Corresponding author: Tel.: +390110904508; fax: +390110904499.
E-mail addresses: valerio.loverso@polito.it, valerio.loverso@gmail.com (V.R.M. Lo Verso).

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solutions, have on energy savings concerned with electric lighting. Therefore the need for both simple and detailed methods to estimate the energy consequences of different design alternatives in the earlier design phases or at the end of the design process is increasing in the sector of daylighting and electric lighting design as well.

Nowadays, the available tools to estimate daylighting and/or the energy demand for lighting in buildings are mainly referrable to two different categories: simplified tools (rules of thumbs, manual calculation methods from standards, etc.) or dynamic climate-based simulation software. The use of simplified methods is predominantly rooted in designer habits; nevertheless, the need for a greater accuracy in building design has been shown by their inability to provide enough accurate information about sufficient daylighting, environmental lighting quality and about the consequences of daylighting solutions on building energy performance. As an example, for the calculation of the electric lighting energy requirements for buildings the European Standard 15193 [6] proposed a simplified calculation methodology to be used for certification purposes. The calculation method is a table-based approach, which uses empirical values and relies on a series of simplified assumptions, the most important among them being the use of the daylight factor to determine the daylight availability within a space. In general the most significant drawbacks of simplified methods pertain to their inability to assess the dynamic behaviour of daylight, to consider the local weather conditions or the influence of direct solar radiation and therefore to their inability to estimate the environmental or energy performance over a whole year.

The need for an accurate estimation of building energy performance led to advancement in numerically analysing the overall performance of indoor spaces. This advancement include a trend away from static and towards dynamic, climate based simulations in general in the building performance analysis and in particular also in the lighting field [7–12]. However, the software used for climate-based daylighting simulation and for calculating the consequent energy use for electric lighting are largely unused by designers and practitioners, partly because the existing standards are still based on traditional metrics (e.g. the daylight factor to estimate the daylight contribution to indoor lighting) and partly because the software for climate-based modelling is not always within the reach of all designers due to prohibitively long computation times and too complicated simulation process [11,13,14]. In the lighting field, softwares such as Daysim [15], Radiance [16], EnergyPlus [17] or Spot [18] are available, free-of-charge, for daylighting and energy simulations, but they require high user expertise to correctly define the input and the simulation parameters and also to correctly interpret the simulation results [11]. Furthermore, this kind of simulation-based daylighting and energy analysis is mainly devoted to more advanced stages of the design process, when detailed 3D models of the design solution are available. In general, it could be said that there is a lack of simple, but enough accurate and therefore climate-based prediction tools to be used by the design team for the optimisation of designs in the conceptual design phase, so as to base the first but crucial decisions about the building shape and orientation, window sizes and glazing and shading systems characteristics etc. also on the resulting final energy consumption of the lighting systems.

The requirement of simplified, quick to use and, if possible, interactive design tools to optimise the complex building design process is becoming more and more evident [19]. An example in the lighting field is the development of a tool called Lightsolve that is intended to become an interactive expert system for daylighting design exploration. The system would allow designers to interactively determine the design changes most likely to improve performance for a given design and it consists of two major components: a daylighting knowledge-base which contains information on the effects of different design conditions of daylighting performance and a fuzzy rule-based decision-making logic which is used to determine the most effective design changes [20–22]. As for daylighting calculation the tool is based on a simulation engine, which calculates annual performance metrics using 3D models and a simplified climate-based lighting analysis. [23–25].

Within this frame, this paper presents a study aimed at developing a simplified, still climate-based, evaluation tool to assess the electric lighting energy demand of rooms in the earliest schematic design phase. The study is based on a parametric analysis carried out using Daysim to calculate the energy demand for electric lighting within a considered room and its variation in response to the variation of the design site as well as of some room features, such as orientation, external obstruction, room depth, window size and visible transmittance, target illuminance and installed electric lighting power density. Furthermore, the impact of a daylight responsive lighting control system with respect to manual on/off control was also considered. The developed tool is a mathematical model to link the annual energy demand for lighting with all the main aspects which influence the daylight availability for a building and hence its electric lighting energetic performance: latitude, orientation, room-depth and width, window-to-wall ratio (WWR), sky angle which can be 'seen' by the window due to surrounding obstructions and lighting control system. Such a model could be useful for a quick and progressive optimisation of the first choices concerned with the building mass, shape, orientation, glazing and shading systems and to predict the associated energy demand for lighting.

Similar approaches have been followed in studies of other researchers. In this regard, Moret et al. [26] recently proposed a mathematical model to predict the impact of daylight harvesting strategies on building energy savings for lighting, cooling and heating, while Fonseca et al. [27] and Wong et al. [28] used an approach based on multivariate non-linear regression techniques via an artificial neural network ANN. The model developed by Fonseca et al. is to predict the impact of daylighting on building final energy requirement and was created starting from Daysim and Energy Plus simulations of a building located in Florianopolis, Brazil, while the model developed by Wong et al. is to predict the daily building energy demand for lighting, for cooling and for heating (and for the total energy demand, accounting for all the three individual contributions), starting from Energy Plus simulations of a building located in Hong Kong.

3. Methodology

The methodology adopted in this study is based on a series of statistical analyses which were applied to the results of a huge number of simulations carried out to estimate the energy demand for lighting for a room whose characteristics were parametrically changed. In the following subsections, the characteristics of the parametric study and the subsequent statistical analyses are described.

3.1. Description of the parametric study

The research carried out to develop the mathematical models has gone through different phases.

As a first step, the parameters influencing the daylight amount and the related electric lighting energy need for an indoor space were identified. Therefore the annual daylighting conditions and energy need were analysed, through the dynamic lighting simulations, for several configurations of a target room. Daysim, a RADIANCE-based software that calculates daylight through a dynamic climate-based annual simulation, was used for this purpose. A single room was used as 'case study'. Its width, height and