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A simple and accurate model for the design of public lighting with energy efficiency functions based on regression analysis

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ABSTRACT

In this study, new relationships between the energy efficiency of street lighting systems, street width, and luminaire height were derived from the analysis of a large sample of outputs, generated with a software application widely used for lighting design. The result was a quadratic polynomial that perfectly fit the relationships obtained and whose coefficients characterize each type of luminaire. This greatly simplifies the design of lighting facilities because it only uses one equation, but at the same time, takes all necessary variables into account. The procedure maximized the energy efficiency of the street lighting systems, as far as conditions allowed, and greatly facilitated the calculation of the parameters of a basic lighting installation, according to CIE (International Commission on Illumination) recommendations.

1. Introduction

Energy efficiency in public lighting installations has become a topic of considerable interest in recent years. Energy-efficient installations should always fulfil recommended *average illuminance* values to ensure visual comfort and safety [1,2]. Other important areas of study are the financial and economic aspects of public lighting, which are also the focus of active research [3,4]. However, from both perspectives, optimal lighting installations can only be achieved if visual accuracy and energy efficiency are addressed from the very beginning in the project design phase. Even though computer programs for public lighting design can achieve uniformity and obtain the average illuminance values in regulations and guidelines, none of these software applications includes energy efficiency as a design parameter for lighting.

Previous studies [5,6] have shown that optimisation algorithms are able to solve problems with more than one target. A quick and reliable method was applied to obtain optimised parameters of a lighting installation in terms of energy efficiency and illuminance uniformity, a quantitative parameter directly related to the quality of a lighting facility. Such studies show that there is a linear relationship between certain key parameters in public lighting. The results thus provide a theoretical way of calculating these parameter values with optimal efficiency. However, since optimisation algorithms are extremely complex tools, it is often necessary for engineers to pay more attention to the meaning of the output than to the problem itself, namely, the lighting of a given road or street.

More concretely, in a previous study, an optimization method for the design of road lighting was applied [5]. This method was based on multi-objective evolutionary algorithms whose target variables were energy efficiency and uniformity. It was necessary to find an acceptable compromise between these variables since when one of them improved, the other inevitably worsened. Although the results obtained with this method were accurate, the calculations required a complex code and the response time was long. Furthermore, the end results involved not one solution but many. It was then up to the designer to choose the best solution for his/her purposes.

In subsequent research [6], the methodology used to obtain the energy-efficient design of public lighting involved two linear equations. This was faster and simpler in comparison to [5]. Although this model was ideal for a technician without a high level of expertise in illumination, it was still somewhat less accurate than the one based on evolutionary algorithms [5].

For this reason, this study focused on formulating a simple procedure to obtain accurate energy-efficient solutions for road lighting design. To attain this goal, the tool used was DIALux [7], a

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well-known free computer application familiar to lighting engineers throughout the world.

In an initial phase, DIALux generated all the possible solutions for lighting streets of different widths with four types of luminaire (Metal Halide, Led, High Pressure Sodium and High Pressure Mercury lamps) of different power, provided by randomly selected manufacturers. When the solutions that complied with CIE (International Commission on Illumination) recommendations were isolated, the result was an almost perfect correlation between efficiency (ε) and the width-height ratio by means of a simple quadratic polynomial, which explicitly included: (i) the rest of the lighting parameters; (ii) average desired value of the lighting magnitude (illuminance E_{av} or luminance L_{av}); (iii) spacing between poles (S); (iv) arrangement of luminaires (one-sided, two-sided coupled and staggered).

Accordingly, for each luminaire, only one equation was derived, which could be used to calculate the basic parameters of any street lighting installation. These equations are very important because they guarantee, insofar as possible, the highest energy efficiency while simplifying the design in the early stages. The results of this research thus led to an innovative method that is more accurate, simpler and quicker than other more conventional methods for road lighting design. It also includes energy efficiency as a decision-maker, as well as the level of lighting and uniformity required.

The rest of the paper is organized as follows: Section 2 describes the background of street lighting and the energy classification of these installations. Section 3 provides an explanation of the materials and methods used to obtain the model. Section 4 presents the results and discusses them in the context of various application examples; and finally, Section 5 lists the most important conclusions that can be derived from this research.

2. Roadway lighting

Roadway lighting installations are characterized by geometrical parameters as well as by the light distribution of the luminaires and their light sources. The requirements for the lighting performance of such installations have been specified by the CIE. Performance level is calculated as the values of certain technical light parameters such as illuminance, $E = d\phi/ds$ (received luminous flux per unit of surface) and luminance (emitted luminous flux within a given solid angle per unit of surface in a given direction). This study focuses on both criteria, since illuminance is applicable to streets and is independent of the reflection factor of the pavement. In contrast, luminance is applicable to highways or other roads where there is a considerable area of unobstructed vision, and where the optical characteristics of the pavement must thus be specified.

In any case, the relationship between luminance and illuminance is a factor called the luminance coefficient that depends on the surface element in a given direction. This coefficient is calculated as:

$$q = \frac{L}{E} \quad (1)$$

Along with these magnitudes, there is a parameter called *overall uniformity* (based on the illuminance or luminance magnitude) which permits the quantification of lighting homogeneity and therefore the quality of the installation, defined as:

$$U_0 = \frac{X_{\min}}{X_{av}} \quad (2)$$

where X_{min} is the minimum value (illuminance or luminance) calculated, and X_{av} is the average value of the corresponding luminous parameter.

The energy efficiency of the lighting installation can be defined as follows:

$$\varepsilon_X = \frac{A_T X_{av}}{P_T} \quad (3)$$

where A_T is the total illuminated surface of the street; P_T is the total electrical power installed, including the light sources and electrical auxiliary devices; and X_{av} is the average value (illuminance or luminance) on the ground. This parameter can also be expressed as a function of individual rectangles influenced by each luminaire as shown in Fig. 1:

$$\varepsilon_X = \frac{A\,X_{av}}{P} \quad (4)$$

where A is the surface of an individual rectangle (see Fig. 1) [6], and P is the electrical power consumed by one luminaire, including its light sources and electrical auxiliary devices.

International standards recommend the overall uniformity of public lighting should be greater than 0.2 [1]. Nevertheless, no overall requirement is given for efficiency, which must simply be as high as possible.

2.1. Definition of lighting classes

In the same way as with the technical parameters, street lighting classes in the CIE recommendations are based on luminance and illuminance criteria. Luminance is identified with the ME series class (relevant to the main roads used for motor vehicle traffic), whereas illuminance is identified with P and CE series classes (affecting all other areas, which include "conflict areas" and low speed areas) as shown in Table 1.

Specifically, the P series is relevant to pedestrians and pedal cyclists on footways, cycle ways, emergency lanes, and other road areas lying separately along the carriageway of a traffic route, residential roads, pedestrian streets, etc., whose lighting criteria are based on average illuminance, ranging from 2 to 15 lux.

The CE series is applicable to motor vehicles when they are in conflict areas such as shopping streets, complex intersections, roundabouts, and queuing areas. It is also relevant to pedestrians and cyclists. Lighting criteria are based on average illuminance ranging from 7.5 to 50 lux.

Finally, the ME series is applicable to high-speed roads whose lighting criteria are based on luminance ranging from 0.3 to 2 cd/m^2. In any case, the relationship between illuminance and

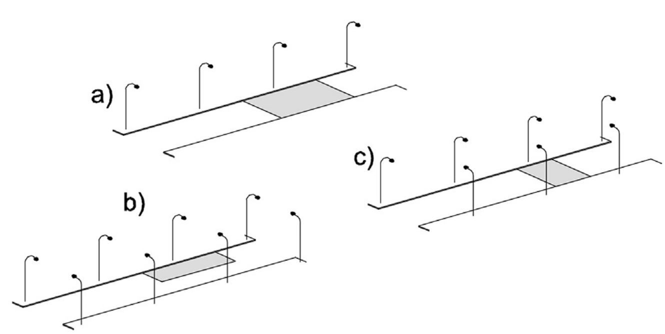

Fig. 1. One-sided (a), two-sided coupled (b), and two-sided staggered (c) installations with individual rectangles influenced by each luminaire according to the arrangement [6].