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A new methodology for calculating roadway lighting design based on a multi-objective evolutionary algorithm

Daniel Gómez-Lorente *, O. Rabaza, A. Espín Estrella, A. Peña-García

Department of Civil Engineering, University of Granada, Severo Ochoa Str. s/n, 18071 Granada, Spain

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ABSTRACT

This paper presents a new method for calculating the design of roadway lighting. Apart from its accuracy, this method, which is based on a multi-objective evolutionary algorithm, has the added advantage of enhancing the energy efficiency of lighting installations. This is positive because the economic use of energy resources is evidently a priority in the world today. In our study, an exhaustive calibration process was used to fine-tune the accuracy and precision of the new method presented. The results obtained were then compared with those of DIALUX, a well-known free software program that is frequently used for the design of lighting installations. In the second phase of this research, the lighting installation was made more complex in order to verify the applicability of this new method to a wide range of different contexts.

1. Introduction

The design of roadway lighting can be regarded as a continuous optimization problem that is solvable with evolutionary algorithms (EAs). These algorithms (Eiben & Smith, 2003; Fernandez, Garcia, Luengo, Bernado-Mansilla, & Herrera, 2010; Garcia & Herrera, 2009) have been instrumental in solving continuous optimization problems in a wide variety of disciplines and areas, such as energy engineering (Alonso, Amaris, & Alvarez-Ortega, 2012), structural mechanics (Mezzomo, Iturrioz, Grigoletti, & Gomes, 2010), and image treatment (Abbasgholipour, Omid, Keyhani, & Mohtasebi, 2011). EAs have performed well in these contexts, where they have been able to successfully deal with complex problems with linear or non-linear cost functions.

Nevertheless, such algorithms have not been widely applied to lighting (Corcione & Fontana, 2003; Zou & Li, 2010), where the distribution of luminaires in exterior or interior lighting installations is generally calculated with software applications based on Finite Elements, Monte Carlo methods, or Linear Optimization (Pachamanov & Pachamanova, 2008). Fortunately, this state of affairs has begun to change, and there is now increasing interest in optimizing all types of lighting, especially since lighting has an incalculable impact on human safety, ergonomics, energy savings, and even human physiology and psychology. However, until now most studies have only provided partial solutions without attacking the core of the problem, namely, the lighting itself.

This paper describes a calculation method for the distribution of roadway luminaires, which is entirely based on EAs. Once developed, this method was calibrated by comparing its results in a wide variety of situations with the results of DIALUX, a well-known free software program.

The algorithm used in our study is the multi-objective evolutionary algorithm (MOEA) (Coello, Veldhuizen, & Lamont, 2002; Deb, 2001), which starts with a set of random solutions known as the initial population. Each individual (chromosome) in the population represents a solution to the optimization problem. In each generation, individuals are evaluated with a fitness function (fitness). Based on this value, certain individuals (parents) are selected. The probability of selecting an individual is related to its adaptability, which means that there is a greater probability of selecting the best individuals. Then, a number of genetic operators are applied to the parents to produce new individuals that will be part of the new population. This process continues in an effort to obtain increasingly better solutions until a stopping criterion is satisfied.

This paper proposes a more efficient MOEA, which we have called NSGA-II. This algorithm incorporates mechanisms specifically conceived to deal with roadway lighting optimization and has the following objectives:

- To maximize the overall illuminance uniformity, U_0.
- To maximize the installation efficiency, ε.

In the examples given, the algorithm is used to select and distribute roadway lighting properties (i.e., the height of the lamps and the spacing between them) in such a way as to maximize these two objectives. Both properties are part of the solution to the

* Corresponding author. Tel.: +34 958 249 435; fax: +34 958 246 138.
E-mail addresses: dglorente@ugr.es (D. Gómez-Lorente), ovidio@ugr.es (O. Rabaza), aespin@ugr.es (A. Espín Estrella), pgarcia@ugr.es (A. Peña-García).

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Table 1
$I(C,\gamma)$ Luminous intensities.

C 0°	*C* 15°	*C* 30°	–	*C* 360°
0°	*I* (0°,0°)	*I* (15°,0°)	*I* (30°,0°)	*I* (360°,0°)
5°	*I* (0°,5°)	*I* (15°,5°)	*I* (30°,5°)	*I* (360°,5°)
10°	*I* (0°,10°)	*I* (15°,10°)	*I* (30°,10°)	*I* (360°,10°)
–				
90°	*I* (0°,90°)	*I* (15°,90°)	*I* (30°,90°)	*I* (360°,90°)

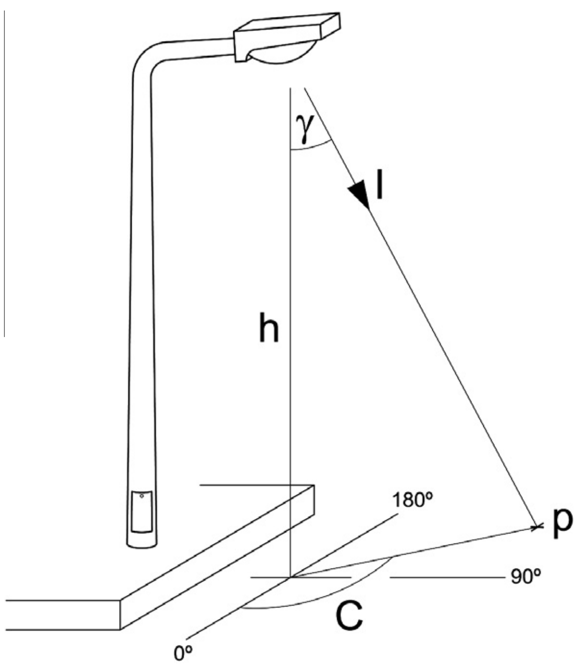

Fig. 1. *C*–γ Coordinate system.

problem in which the overall illuminance uniformity and the installation efficiency are identified and specified. Our experimental study also compared the NSGA-II results with those obtained with DIALUX.

The rest of the paper is organized as follows: Section 2 describes the background of road lighting; Section 3 explains how NGSA-II can be used to optimize roadway lighting; Section 4 discusses roadway lighting criteria and analyzes the results obtained, and Section 5 summarizes the conclusions that can be derived from this research.

2. Roadway lighting

2.1. Background and positioning

The main objective of road lighting is to produce safe and comfortable vision at night. The effective use of public lighting on roadways evidently helps to protect drivers and improve vehicle traffic by making it more fluid. In addition, it also provides economic benefits stemming from the rationalization of illumination levels. When levels are optimal, they provide sufficient illumination to reduce night-time accidents. Yet, at the same time, illumination should not be excessive since sustainable lighting installations should minimize electricity consumption.

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 International Commission on Illumination (CIE, 2010). The performance level is calculated as the values of certain criteria known as light technical parameters. For example, certain light technical parameters are illuminance-based (where the illuminance is the luminous flux received per unit of surface) whereas other parameters are luminance-based (i.e., the emitted luminous flux within a given solid angle per unit of surface in a given direction), taking into account the relevant parameters for the visual tasks. Ideally, luminaires for roadway lighting should ensure a spatial redistribution of the luminous flux of the lamps inside them. In this way, the required average illuminance of the road surface as well as the other parameters specified by the CIE are attained with a minimum luminous flux, and therefore, a minimum electrical power consumption.

An important criterion for the roadway lighting design in this article was to achieve a compromise between the maximum overall illuminance uniformity of the road surface and the maximum energy efficiency of the installation, while maintaining a constant mean illuminance. The overall illuminance uniformity is:

$$U_0 = \frac{E_{\min}}{E_{av}} \tag{1}$$

where $E_{\min}$ is the minimum illuminance value calculated over all units between the next two lighting fittings, and where E_{av} is the average illuminance. The maximum energy efficiency of the installation can be represented as follows:

$$\varepsilon = \frac{A \cdot E_{av}}{P} \tag{2}$$

where A is the illuminated surface, and P is the total electrical power installed, including the light sources and the electrical

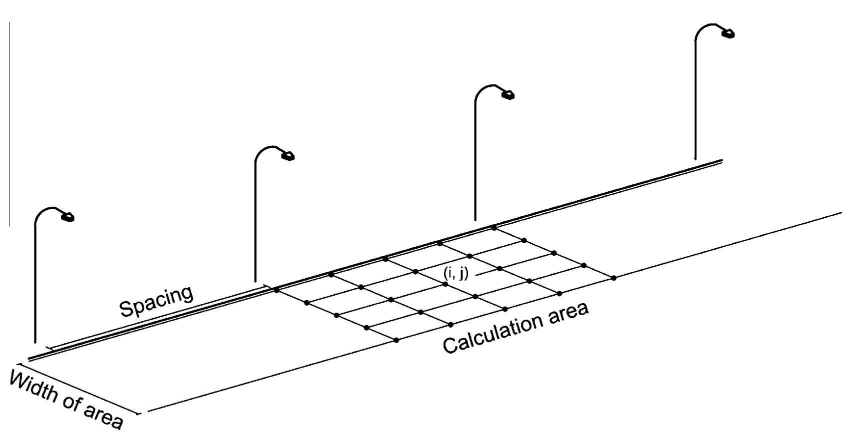

Fig. 2. One-sided installation.