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A simple method for designing efficient public lighting, based on new parameter relationships

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ABSTRACT

New parameter relationships for public lighting design (i.e. average illuminance, luminaire spacing, and mounting height) were calculated from a large sample of data sets optimized with a multi-objective evolutionary algorithm. Optimization criteria included maximum energy efficiency and overall uniformity. The relations thus derived are a simple and elegant method for designing any type of public lighting installation without the need to use complex, expensive and/or unavailable software. It would therefore be desirable that manufacturers include such parameters in the product datasheet in order to make the calculation easier.

1. Introduction

The main goal of public lighting is to protect people and goods, but because of the current global financial crisis, such lighting systems must also be sustainable. Sustainability is thus a crucial issue even though the very subjectivity of this concept makes it difficult to define. Each year, developed countries consume huge quantities of electricity for street lighting. An excellent parameter to measure sustainability is that of energy efficiency.

In recent years, the energy efficiency of public lighting installations has become an important area of focus. Currently, software applications for public lighting design are geared to achieve uniformity and obtain the average illuminance values recommended by the International Commission on Illumination (CIE, 2010). Nevertheless, the energy efficiency of the installation itself is not contemplated by any of these computer programs. In addition, such applications do not generally allow users to select the desired level of uniformity for the installation. It goes without saying, however, that accurate values for the energy efficiency and uniformity of general lighting, in combination with the required average illuminance values in national legislation (Real Decreto 1890/2008, 2008), would guarantee a homogeneous and sustainable lighted area with an optimal amount of light.

Previous work (Gómez-Lorente, Rabaza, Espín Estrella, & Peña-García, 2013) has demonstrated the viability of using multi-objective evolutionary algorithms (MOEAs) (Coello, Veldhuizen, & Lamont, 2002; Deb, 2001) to obtain the parameters for a lighting installation with maximum uniformity and efficiency, based on a given set of luminaire characteristics. However, this pioneering work must still be adapted to the needs of the engineer who is in charge of designing safe and sustainable lighting.

This paper presents the results of a study that applied a well-known MOEA called Non-dominated Sorting Genetic Algorithm NSGA-II (Deb, Pratap, Agarwal, & Meyarivan, 2002) to the optimization of public lighting. The solutions obtained with the algorithm are represented as points on a front. These data sets were used to perform a linear regression analysis and thus ascertain relations pertaining to luminaire spacing, height, and illuminance, which are some of the main outputs in street lighting calculations. The regression coefficients obtained by the fit are the characteristic parameters for a given luminaire model in each type of public lighting configuration. Therefore, with these coefficients, it is relatively simple to design efficient street lighting. The linear equations used are shown in (1):

$$\begin{aligned} H &= a \cdot E_{av} + b \\ S &= c \cdot E_{av} + d \end{aligned} \qquad (1)$$

where a, b, c, and d are the luminaire parameters; E_{av} is the desired average illuminance, depending on the lighting class (CIE, 2010); S is the spacing between luminaires; and H is the mounting height of the luminaires.

The rest of the paper is organized as follows: Section 2 describes the background of roadway lighting and the energy classification of these installations. In Section 3 we present the MOEA used, the experimental framework, we discuss the results obtained and we show an analysis of relationships between luminaire height, luminaires spacing and average illuminance. Section 4 presents the model obtained and an example of application and finally, in Section 5 we summarize our conclusions.

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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 performance of such installations have been specified by the CIE, where the performance level is calculated according to the values of certain criteria known as light technical parameters. Light technical parameters are illuminance-based (where the illuminance is the luminous flux received per unit of surface). In contrast, other parameters are luminance-based (i.e. based on the luminous flux emitted within a given solid angle per unit of surface in a given direction), taking into account the relevant parameters for the visual tasks. Ideally, the luminaires for roadway lighting should ensure a spatial redistribution of the luminous flux of the lamps inside them.

The parameters in this research study are illuminance-based. The first parameter is the overall illuminance uniformity, which is directly related to the quality of the roads illumination because low uniformity ratios imply frequent changes of contrasting high- and low- lit road segments and it causes enormous eye discomfort, leading to stress and tiredness and therefore jeopardizing road safety. The illuminance uniformity is defined by (2):

$$U_0 = \frac{E_{\min}}{E_{av}} \tag{2}$$

where E_{min} is the minimum illuminance value calculated for all units between the next two lighting fittings; and E_{av} is the average illuminance. The energy efficiency of the lighting installation, which can be easily deduced, is:

$$\varepsilon = \frac{A_T \cdot E_{av}}{P_T} \tag{3}$$

where A_T is the total illuminated surface; and P_T is the total electrical power installed, including the light sources and the electrical auxiliary devices. This parameter can also be expressed as a function of individual rectangles influenced by a given luminaire as shown in (4):

$$\varepsilon = \frac{A \cdot E_{av}}{P} \tag{4}$$

where A is the surface of an individual rectangle (see Fig. 1); E_{av} is the average illuminance on the ground; and P is the power consumed by the entire lighting system, including lamps and ballasts.

Regarding both parameters, international standards for public lighting recommend an overall illuminance uniformity greater than 0.4. However, there is no overall requirement for efficiency, which must simply be as high as possible.

Computer applications commonly used for the design of lighting systems generally base their calculations over the characteristics of the street to be illuminated (i.e. street dimensions, desired average illuminance, etc.) as well as the configuration of the installation (one-sided, two-sided staggered, two-sided coupled, etc.), being the main results of the calculation the spacing between luminaires, height of luminaires and overall illuminance uniformity. Although there are also other types of output (e.g. glare, graphics, cylindrical illuminance, etc.) none is as common used as those mentioned previously.

Notwithstanding, energy efficiency has become an increasingly significant parameter that must also be considered. Unfortunately, it is somewhat difficult to calculate since it cannot be obtained by the usual lighting design software, and, in fact, is rarely considered in the lighting design optimization process. This is all the more surprising since in many countries, lighting installations are classified, depending on their efficiency. For this reason, in previous research (Gómez-Lorente et al., 2013), a MOEA was used to maximize energy efficiency for one overall illuminance uniformity in order to find the best solutions for a public lighting installation.

2.1. Definition of lighting classes

In the same way as with the technical parameters, street lighting design in the CIE recommendations is based on luminance and illuminance criteria. Luminance is relevant to roads main used for motor vehicle traffic, whereas illuminance affects all other areas, which include "conflict areas", such as junctions, minor and residential roads, urban centers, and foot and cycle paths. In such situations, the application of lighting criteria is based on average illuminance and its uniformity, which correspond to the CE series lighting classes, ranging from 7.5 to 50 lux of horizontal plane illuminance as it is shown in Table 1. These CE classes are applicable to motor vehicles when they are in conflict areas such as shopping streets, complex intersections, roundabouts, and queuing areas. They are also relevant to pedestrians and cyclists.

P series classes (see Table 2) are 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 road, pedestrian street, etc.

The average illuminance for lighting class series are expressed as the "minimum average illuminance maintained", though it is well-known that average illuminance for each lighting class refers to intervals.

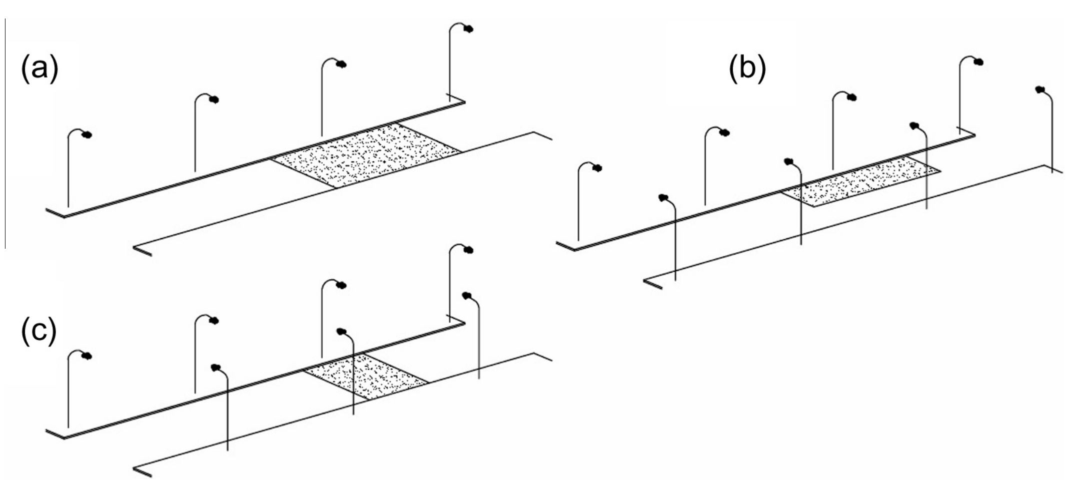

Fig. 1. One-sided (a), two-sided coupled (b) and two-sided staggered (c) installations with the individual rectangle for each luminaire is represented.

Table 1
Lighting class CE series: conflict areas.

Lighting class	Horizontal illuminance	
	Average illuminance (lux)	Uniformity
CE0	>50	0.40
CE1	30	0.40
CE2	20	0.40
CE3	15	0.40
CE4	10	0.40
CE5	7.5	0.40

Table 2
Lighting class P series: pedestrian and low speed areas.

Lighting class	Horizontal illuminance	
	Average illuminance (lux)	Minimum illuminance
P1	>15	3
P2	10	2
P3	7.5	1.5
P4	5	1
P5	3	0.6
P6	2	0.4

Table 3
Energetic classification of a street lighting installation.

Energy category	SE W/(lux m^2)
A	0.000–0.014
B	0.015–0.024
C	0.025–0.034
D	0.035–0.044
E	0.045–0.054
F	0.055–0.064
G	0.065–0.074

2.2. Energy classification of street lighting installations

The approach adopted in this research is based on the Street Lighting Energy Efficiency Criterion (SLEEC) (CEN, 2008) as a whole system indicator, taking into account the efficiency of the lamp, ballast, and luminaire. The formula for the SLEEC indicator depends on the photometric measurement used in the calculation of street lighting for specific road classes. For illuminance-based road classes, the indicator[1] is given by (5):

$$SE = \frac{1}{\varepsilon} \tag{5}$$

where ε is the energy efficiency of the street lighting installation whose parameters are given in Eq. (3). Table 3 shows the energy label categories A–G with target ranges for the SLEEC.

As can be observed in Table 3, the energy categories using the SLEEC indicator are in consonance with the standard EU A–G energy labels in Fig. 2.

3. Analysis of the MOEA output data

The use of single-objective or multi-objective evolutionary techniques to solve lighting problems has become more and more frequent in recent years. For example, mixtures of multiple narrow-band LEDs were optimized with a differential evolution algorithm (Soltic & Chalmers, 2012). MOEAs have also been successfully applied to outdoor lighting systems, as exemplified by the use of genetic algorithms to calculate the optimal lighting for an outdoor (Corcione & Fontana, 2003) tennis court or a football field. The results obtained were then compared to those of more traditional optimization procedures, such as Monte Carlo and gradient methods in order to check that solutions agreed.

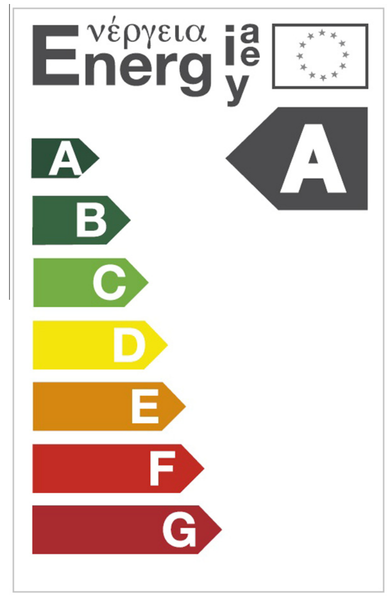

Fig. 2. EU energy class labels. Each color code is associated with a letter from A to G, indicating the electricity consumption of the appliance.

In addition, the MOEA known as Non-dominated Sorting Genetic Algorithm (NSGA-II) in which this work is based, has successfully solved optimization problems related to the color quality of LED lighting, based on the memory color quality metric (Smet, Ryckaert, Pointer, Deconinck, & Hanselaer, 2012).

In general, these examples demonstrated the effectiveness of MOEAs (Deb, 1999; Fonseca & Fleming, 1993) to solve multi-objective optimization problems (e.g. roadway lighting) in which a number of conflicting objective functions must be minimized or maximized (Deb, 2001).

3.1. Optimization process with NGSA-II

As previously mentioned in the introduction, a multi-objective genetic algorithm known as the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was used to maximize the overall uniformity as well as the energy efficiency of street lighting (Gómez-Lorente et al., 2013). In this case, the street dimensions, luminaire characteristics (e.g. spatial light distribution of the luminous flux) and the required illuminance values are input parameters. Our objective was to evaluate the influence of the location and characteristics of the luminaires on the performance of the roadway lighting system. Fig. 3 shows the NSGA-II pseudocode.

NSGA-II used in this study has two functions: one calculates the average illuminance of the street and the other calculates the efficiency in this same street. Concerning the first function, the algorithm computes the surface of the area between two consecutive luminaries on the same side of the street, and after, as seen in Fig. 4 the algorithm makes a meter to meter grid for the whole surface and calculates the value of illuminance in each point of this grid. The average illuminance is obtained as the arithmetical average of all the illuminances in the points of the grid.

On the other hand, in the second function the algorithm just needs the dimensions of the individual rectangle according to the

[1] The *SLEEC* indicator for illuminance is *SE*, whereas the indicator for luminance is *SL*.

```
Initialize population
      Generate random population - size M
      Evaluate objective values
      Assign rank based on Pareto dominance - "sort"
      Generate child population
            Binary tournament selection
            Recombination and mutation
For i=1 to G
      With parent and child population
            Assign rank based on Pareto dominance - "sort"
            Generate sets of nondominated fronts.
            Loop (inside) by adding solutions to next generation starting
            from the "first" front until M individuals found.
            Determine crowding distance between points on each front
      Select points (elitist) on the lower front (with lower rank) that
      are outside a crowding distance
      Create next generation.
            Binary tournament selection
            Recombination and mutation
      Increment generation index
End loop
```

Fig. 3. NSGA-II pseudocode.

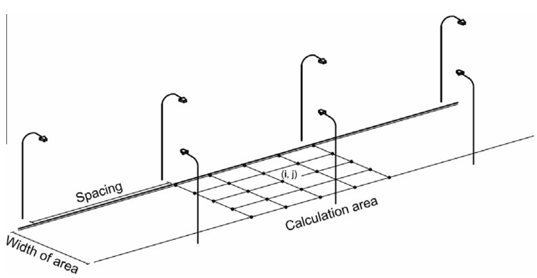

Fig. 4. Calculation area with contributable luminaires.

distributions shown in Fig. 1 (one-sided, two-sided coupled or staggered), which must be previously introduced to obtain the energy efficiency as well as the number of luminaries which contribute in the calculation of the illuminance, also necessary.

The individuals in this MOEA are formed by two attributes that are randomly initiated in the first evaluation: the spacing between luminaries and their height. The first, directly affects to the average illuminance (the illuminance is lower with less luminaries) and also to the uniformity, because the higher the number of luminaries, the uniformity is higher. This variable does not have constrains, because the algorithm ignores the solutions with an average illuminance that is different from the required or with very low efficiency, which happens when the spacing is very large or very small.

The attribute corresponding to the height of luminaries is determined by the length of the available supports or poles in the market. So, the algorithm ignores the solutions with unfeasible heights during its search.

Since both objectives are contradictory, the MOEA must keep an equilibrium that allows us to get the most accurate solutions.

MOEA starts with a random population of 100 individuals progressing in each evaluation until the front of optimal solutions is found. An initial number of 100 individuals has been chosen because it is a sample large enough to obtain populated and significative fronts, but not so large to slow the simulations. We have also performed simulations with 150 or 200 individuals, but the only achievement have been curves with more points, nearer from each other, but irrelevant when compared with the obtained model. On the other hand, these trials with more individuals have remarkably raised the computational cost of the algorithm.

Although the variables of the problem have not been constrained, maximum and minimum limits have been established to obtain coherent solutions. The algorithm has been completely free to progress iteratively with the solutions towards the achieved results. The targets under consideration (efficiency and uniformity) are opposite in lighting installations, that is, the raise of one yields to the decrease of the other. For this reason, the obtained curves make sense in an optimization problem.

These curves or "solution fronts" are formed by sets of solutions indicating the most optimal for the problem in the form of graphs on Cartesian axes representing the efficiency and uniformity values of the installation. In order to ascertain the relationships between the parameters of a given lighting installation, this study analyzed these sets of points (Fig. 5) for a street with a single-side, double-side staggered, or double-side coupled luminaire arrangement.

As previously mentioned, the output results of the MOEA shown in Fig. 5 are in the form of fronts that represent the best options for energy efficiency and uniformity (parameter directly related to the quality of the lighting). These solutions are for the same street illuminated by different lighting configurations, each of which used three different light sources: high pressure sodium lamps (HPS) of 70, 100 and 150 W, whose polar intensity diagrams of the luminaires are shown in Fig. 6.

Each optimal solution is directly related to a vector composed of three parameters: (i) luminaire spacing; (ii) luminaire height and (iii) resulting illuminance, which allowed to obtain the Eq. (1).

The outputs of the MOEA in Fig. 5 are in consonance with the definition of installation efficiency given by Eq. (4) and the overall illuminance uniformity given by Eq. (2), where an increase in uniformity implies reduction of spacing between luminaires (i.e. reduction of the surface of an individual rectangle) in order to reduce the frequent changes of contrasting high and low illumination, and therefore produces a corresponding reduction in efficiency.

Based on these data, the objective of this study was to search for common elements that could be used to formulate general expressions. Our hypothesis was that such expressions would presumably lead to a simpler method of the main lighting parameters thus ensuring the efficiency of the installation.

3.2. Relationships between luminaire height and average illuminance

For our study, we extracted the points in Fig. 5 with a uniformity higher than 0.4, whose solutions are shown in Figs. 7–9, scat-

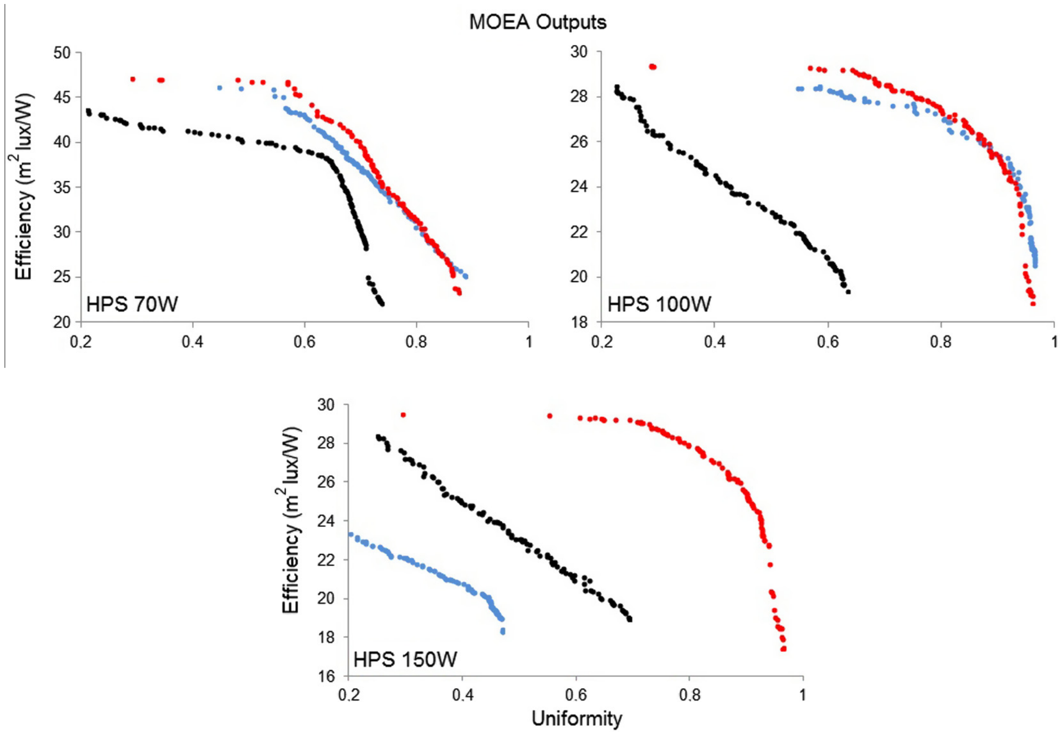

Fig. 5. Outputs of the MOEA for the most typical lighting arrangements; one-sided (black points), two-sided coupled (blue points), and two-sided staggered (*red points*) installations. Each of the points corresponds to an optimal solution in terms of efficiency and uniformity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

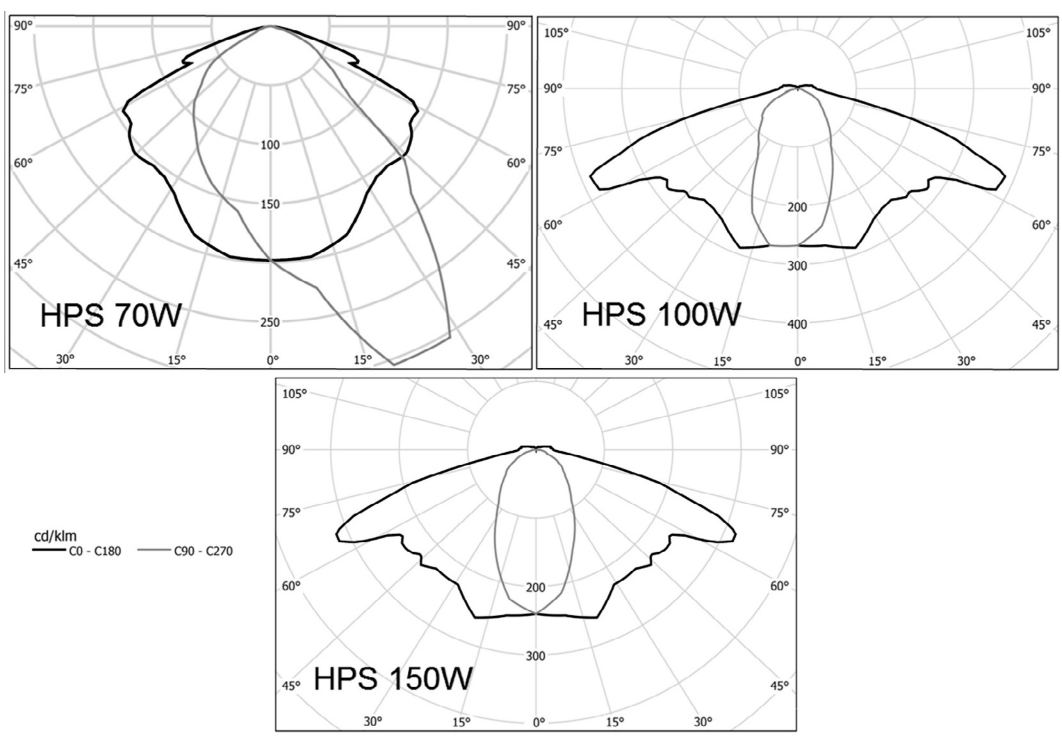

Fig. 6. Polar intensity diagrams of the luminaires of 70, 100 and 150 W high pressure sodium lamps. The luminaires are the same manufacturer.

ter plots in terms of the height of the luminaires and the average illuminance on the street.

Figs. 7–9 show the results of the correlation analysis performed between luminaire height and average illuminance values calculated for high-quality, energy-efficient installations. Linear regression analysis of illuminance and height showed a significant very strong correlation ($R^2 > 0.85$) and a clear trend, because the illuminance increases when the height of the luminaires is reduced.

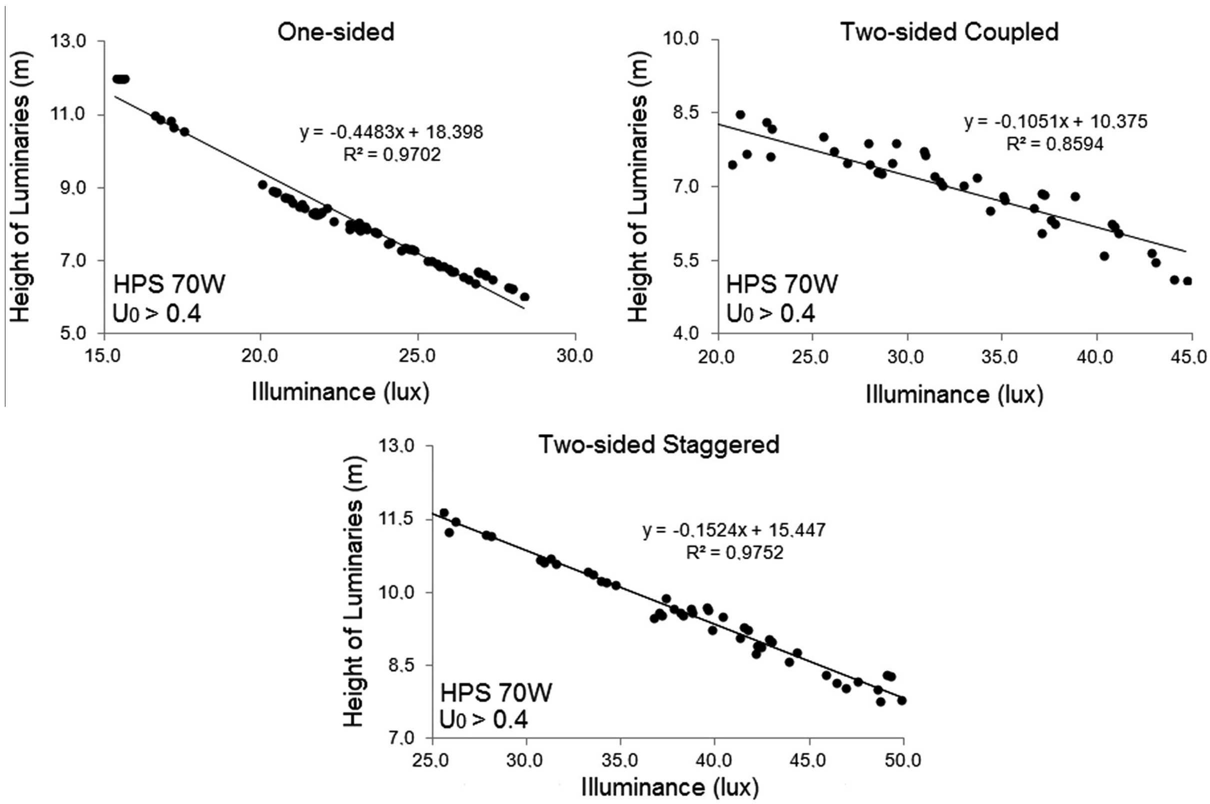

Fig. 7. Linear regression analyses between average illuminance and luminaire height for the HPS 70 W lamp in the most typical lighting arrangements.

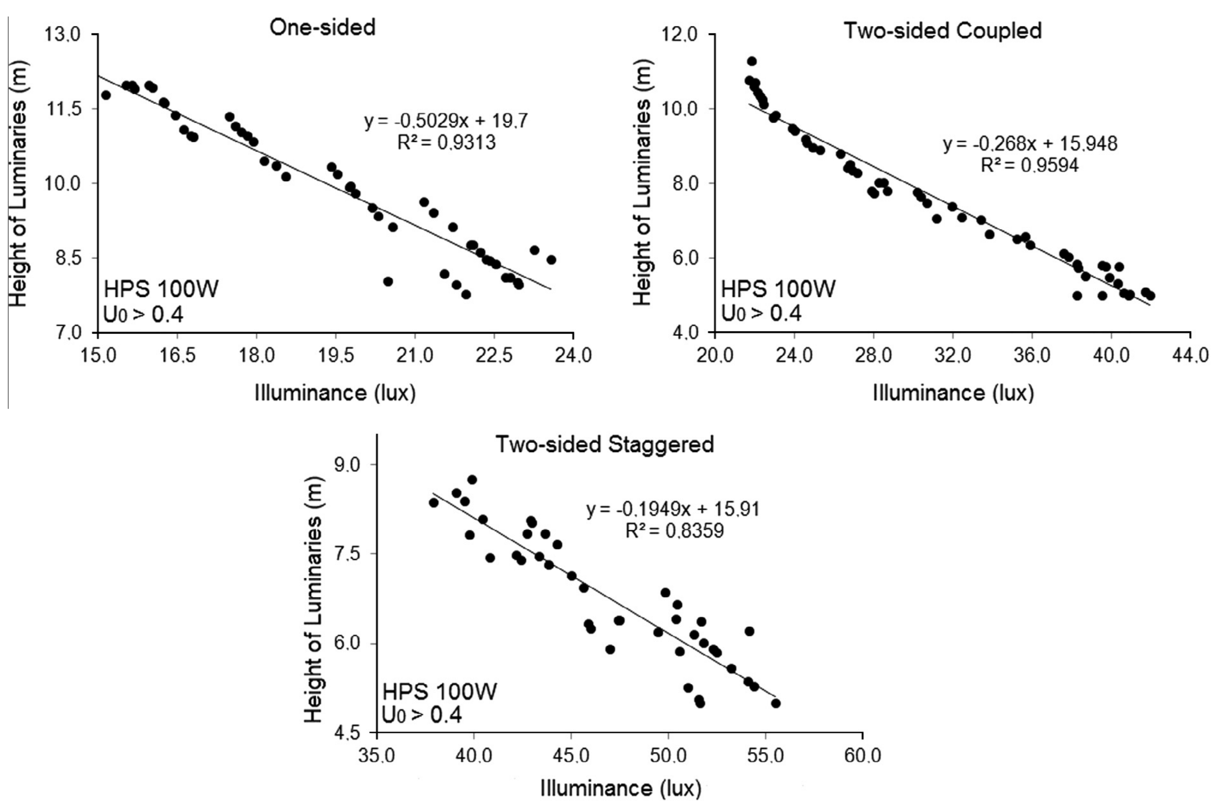

Fig. 8. Linear regression analyses between average illuminance and luminaire height for the HPS 100 W lamp in the most typical lighting arrangements.

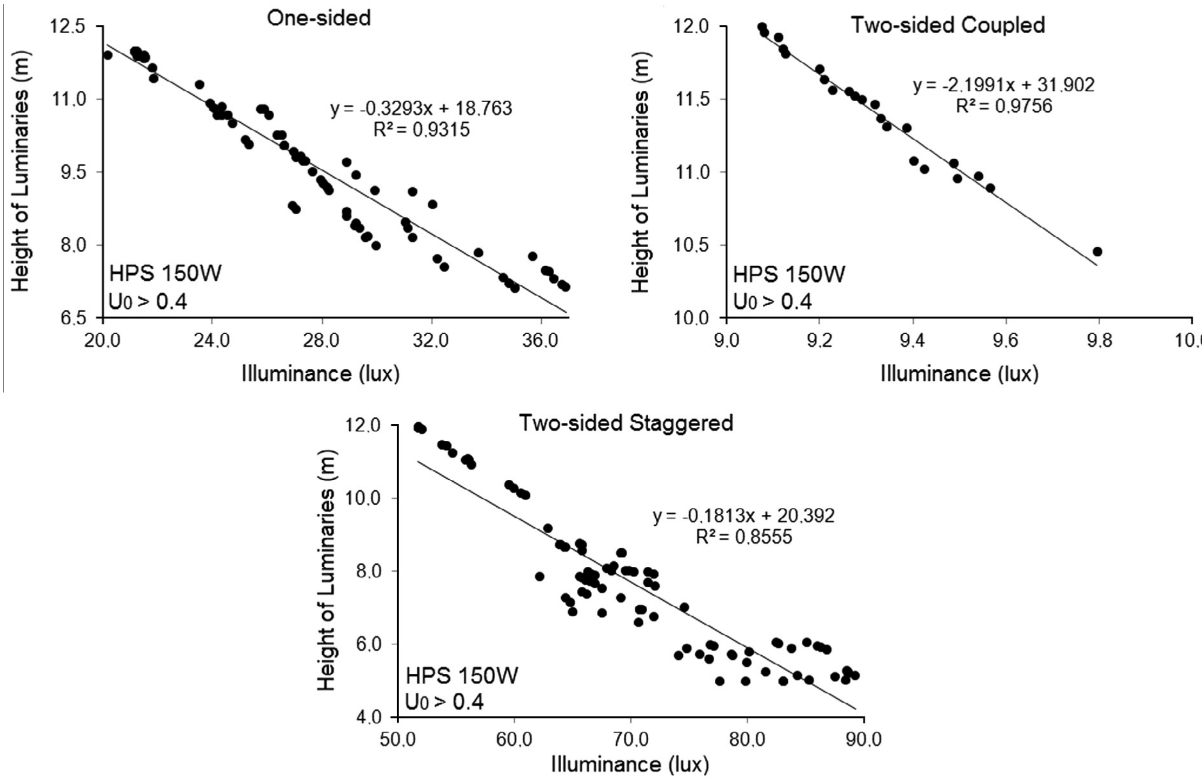

Fig. 9. Linear regression analyses between average illuminance and luminaire height for the HPS 150 W lamp in the most typical lighting arrangements.

Mathematically, the relationships between the illuminance and the height of a single light source is given by (6), expression known as the inverse square law;

$$E\alpha\frac{I}{d^2} \quad (6)$$

where the illuminance E in a point of the road is proportional to the light intensity I emitted by the source and inversely proportional to the square to the luminous source distance d, however, in our case we are referring to the average illuminance of all points of the grid that correspond to calculation area (street width $\times$ spacing) shown in Fig. 4.

The linear trend in Figs. 7–9 is because the solutions obtained with the algorithm have different spacing between luminaries, we must not forget that the spacing between luminaries is a free variable that is not constrained in the optimization process.

3.3. Relationships between luminaires spacing and average illuminance

In the same way as in Section 3.1, the points in Fig. 5 were used to find relationships between luminaire spacing and average illuminance, which are the optimal solutions (in terms of efficiency and uniformity) for both. Scatter plots are shown in Figs. 10–12.

As can be observed in Figs. 10–12, most of the relationship showed a very strong correlation, i.e. $R^2 > 0.85$ for HPS 70 W lamp, $R^2 > 0.65$ for HPS 100 W lamp and $R^2 > 0.87$ for HPS 150 W lamp.

The worse case was in the two-side staggered for HPS 150 W lamp, where relationships showed a weak correlation, however, 90% of the solutions were found between spacing of 10.5 and 13.5 m, therefore the relationship trend is very evident.

Most of the figures, the trend is expected, if the spacing between luminaires decreases the average illuminance increases because more points of light are installed. However, if we look at Fig. 12, the correlation obtained with distribution in staggered the tendency is slightly opposite. This is due to that the height of the luminaires decreases when increases the spacing between them, which is consistent with that observed in the previous section. Like the spacing between luminaires, the height of the light sources is a free variable used by the algorithm to obtain the most efficient solutions.

With respect to the linearity of the results, obviously the regression coefficients would be in some cases a little better if the data conform to non-linear functions, however, the calculation of the variables "H" and "S" would be quite complicated compared to the slight improvement of the adjustment.

In any case, the goal is to establish simple relationships between variables, not to calculate the best possible curve fit, so the solutions used in this study are those in which the trend is most evident.

4. The model

Figs. 7–12 show that when a linear regression analysis is performed, based on NSGA-II results, in most cases, a relationship such as Eq. (1) is obtained. For each luminaire, characteristic parameters (a, b, c and d) were found to ensure maximum efficiency for each type of installation.

Obviously, when the a, b, c and d parameters of the luminaire are known, it is simple to calculate the most important characteristics of the installation (luminaire spacing and luminaire height) based on CIE requirements (overall illuminance uniformity U_0 and average illuminance E_{av}), ensuring that the solution will be the most energy-efficient option.

Another aspect to consider in any decision regarding the distribution of luminaires is the relationship between roadway width and mounting height. Table 4 shows some relationships based on the experience of lighting designers, where generally speaking, a

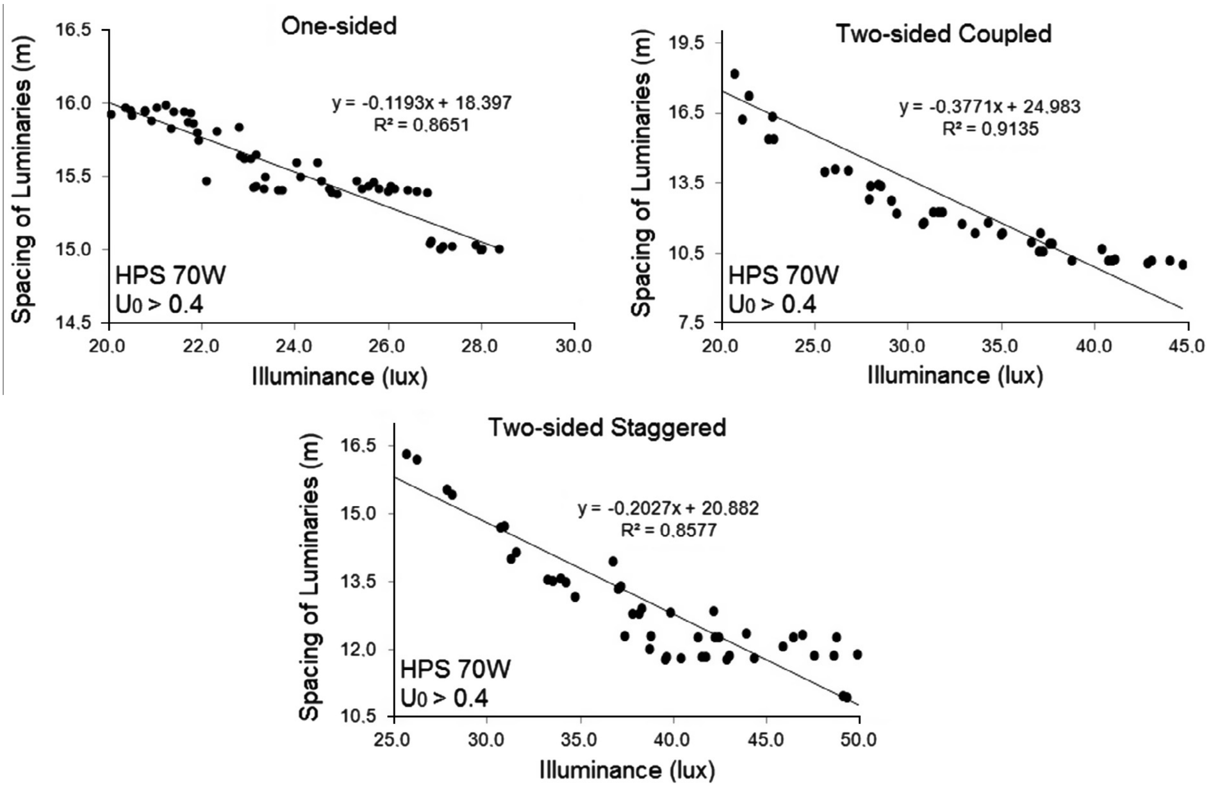

Fig. 10. Linear regression analyses between average illuminance and luminaire spacing for the HPS 70 W lamp in the most typical lighting arrangements.

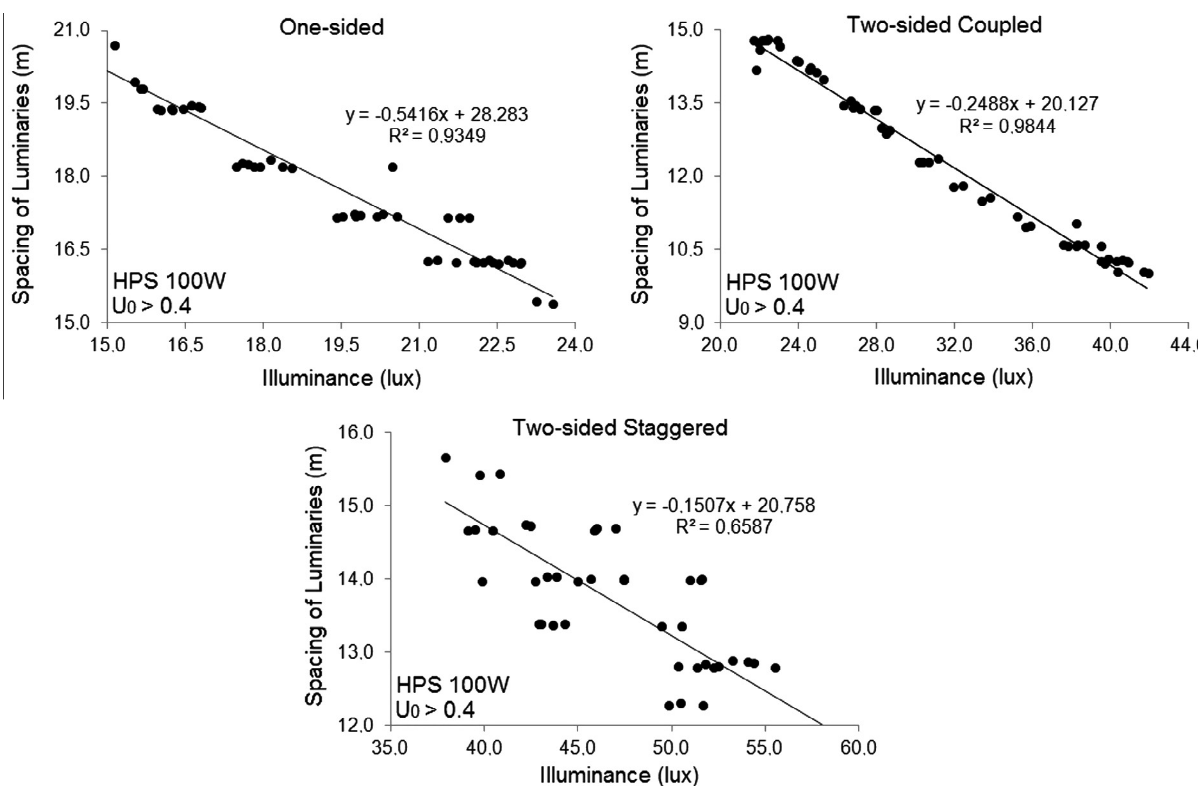

Fig. 11. Linear regression analyses between average illuminance and luminaire spacing for the HPS 100 W lamp in the most typical lighting arrangements.

one-sided installation is preferable when the width of the roadway is less than the mounting height of the luminaires. A two-sided staggered arrangement is preferred when the width of the roadway is 1–1.5 times the mounting height, and a two-sided coupled arrangement is generally the best choice when the width is equal to or greater than 1.5 times the mounting height. Therefore, before

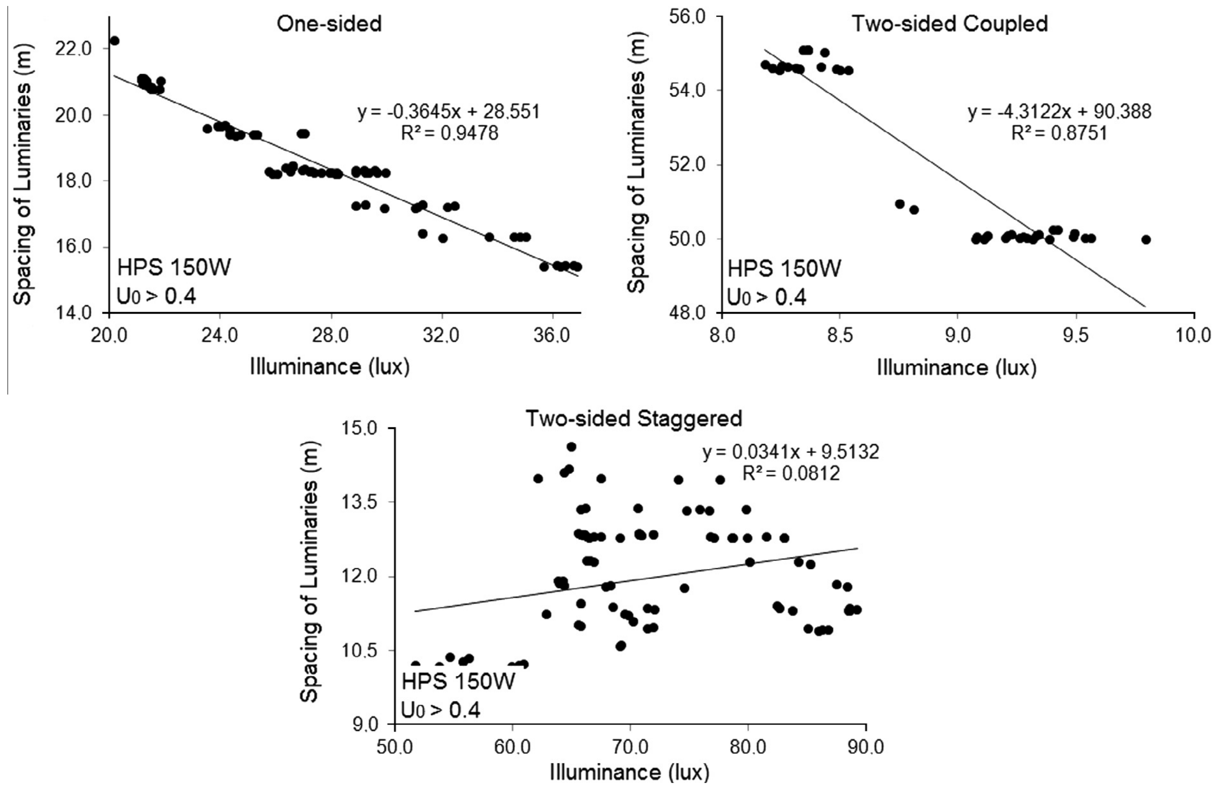

Fig. 12. Linear regression analyses between average illuminance and luminaire spacing for the HPS 150 W lamp in the most typical lighting arrangements.

Table 4
Luminaires configuration as function of the street width and mounting height.

Configuration	Ratio = width/height
One-sided	Ratio < 1
Two-sided staggered	1 ⩽ ratio < 1.5
Two-sided coupled	1.5 ⩽ ratio

Table 5
Characteristic parameters of the HPS 70 W lamp.

Arrangement	$H = a \cdot E_{av} + b$		$S = c \cdot E_{av} + d$	
	a	*b*	*c*	*d*
One-sided	−0.45	18.4	−0.12	18.4
Staggered	−0.15	15.5	−0.20	20.9
Coupled	−0.11	10.4	−0.38	25.0

choosing the arrangement, the mounting height must be calculated for each distribution in order to compare it with the width of roadway.

Tables 5–7 lists the installation parameters for each lamp as derived from the linear regression data.

4.1. Example of application

The model was validated by testing it on a roadway illuminated with HPS 70 W lamps. The lighting class arbitrarily chosen was CE2, where according to Table 1, the recommended average illuminance is 20 lux and the recommended overall uniformity must be $U_0 \geqslant 0.4$. The street width is 7 m and the characteristic parameters of the luminaire are shown in Table 4. Eq. (1) was then applied to calculate the height and the spacing of luminaires (in meters) for each arrangement, whose solutions are summarized in Table 8:

Table 6
Characteristics parameters of the HPS 100 W lamp.

Arrangement	$H = a \cdot E_{av} + b$		$S = c \cdot E_{av} + d$	
	a	*b*	*c*	*d*
One-sided	−0.50	19.7	−0.54	28.3
Staggered	−0.20	15.9	−0.15	20.8
Coupled	−0.27	16.0	−0.25	20.1

Table 7
Characteristic parameters of the HPS 150 W lamp.

Arrangement	$H = a \cdot E_{av} + b$		$S = c \cdot E_{av} + d$	
	a	*b*	*c*	*d*
One-sided	−0.33	18.8	−0.36	28.6
Staggered	−0.18	20.4	0.03	9.5
Coupled	−2.20	31.9	−4.31	90.4

Table 8
Results over a street lighting class CE2 (20 lux). The street width is 7 m.

Configuration	*H* (m)	*S* (m)	Width/height
One-sided	9.4	16	0.75
Two-sided staggered	12.5	16.9	0.56
Two-sided coupled	8.2	17.4	0.85

The ratio between roadway width and mounting height is ∼0.75 in the one-sided arrangement; ∼0.56 in the two-sided staggered arrangement; and ∼0.85 in the two-sided coupled arrangement. As a result, the one-sided arrangement was found to be that which best conformed to the criterion of the ratio between roadway width and mounting height (see Table 4). In addition, the results obtained showed that the one-sided installation was

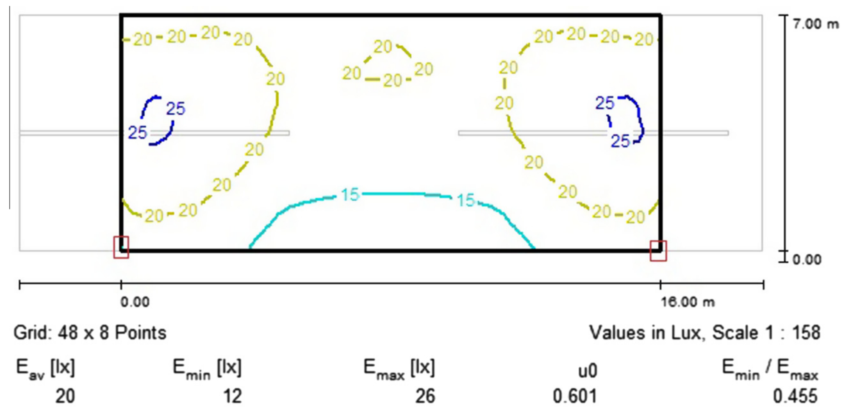

Fig. 13. Simulation result obtained with DIALux for a one-sided installation. The parameters of the design are, 9.4 m mounting height and 16 m spacing between luminaires in a street with 7 m width.

also the best because it is the least expensive in terms of luminaires, lamps, wires etc. The best arrangement is thus a one-sided configuration with 16 m spacing between luminaires and a mounting height of 9.4 m.

To check these results a simulation was made with DIALux (DIAL official, 2013), a lighting engineering free software program. The simulation result is shown in Fig. 13, where spacing between luminaires (16 m) and mounting height (9.4 m) were introduced in a street with 7 m width (inverse problem) as well as luminaires (see Fig. 6) used in the MOEA.

Based on the design parameters entered, the results of the simulation are E_{av} = 20 lux and U_0 = 0.6, which are in consonance with the lighting class CE2 previously selected.

Applying the Eqs. (4) and (5), the SLEEC indicator (including the power consumption of the lamp and ballast for the one-sided installation) gives SE = 0.0348 W/lux/m^2. In this case, the energy category of the one-sided installation is *C*, whereas the indicators for two-sided staggered and the two-sided coupled arrangements are 0.066 and 0.064 W/lux/m^2 respectively. As we can see, the decision in based on Table 4 was successful, because in both these cases the energy category of both is *F*, worse than the proposed solution.

Therefore, for a specific luminaire, this simple method can be used to arrive at a solution that is optimal in terms of energy efficiency and uniformity, and it confirms the accuracy of the configuration choice, which perfectly fits the output of the equations in Table 5.

What happens with a different street width? Suppose the same luminaire with HPS 70 W lamp is installed in a street width of 14 m, after applying the Eq. (1) the results are in Table 9:

According to our model, the mounting height and spacing between luminaires are independent to the width of the street, so we will have the same values for both widths street, 14 and 7 m. As we will see later, this implies that the resulting average illuminance is within the range corresponding to its lighting class and not the "minimum illuminance value maintained". The only parameter to decide the configuration is the width-height ratio, which in this case two-sided staggered and coupled configurations are compatible with the criteria, therefore in this case the more efficient will be the chosen one; two-sided coupled arrangement whose *SE* values according to the model is 0.032 W/lux/m^2.

Based on the preceding calculation, where the mounting height is 8.2 m and the spacing between luminaires is 17.4 m, Fig. 14 shows the simulation result obtained with DIALux, whose final results are E_{av} = 27 lux and U_0 = 0.53.

As previously mentioned, the illuminance value is within the range corresponding to CE2 lighting class, in which $20 \leqslant E_{av} < 30$ lux (see Table 1). The SLEEC indicator including the power consumption of the lamp and ballast is finally 0.024 W/lux/m^2, so the energy category of this installation is *B*.

Table 9
Results over a street lighting class CE2 (20 lux). The street width is 14 m.

Configuration	*H* (m)	*S* (m)	Width/height	*SE* (W/lux/m^2)
One-sided	9.4	16	1.49	0.017
Two-sided staggered	12.5	16.9	1.12	0.033
Two-sided coupled	8.2	17.4	1.71	0.032

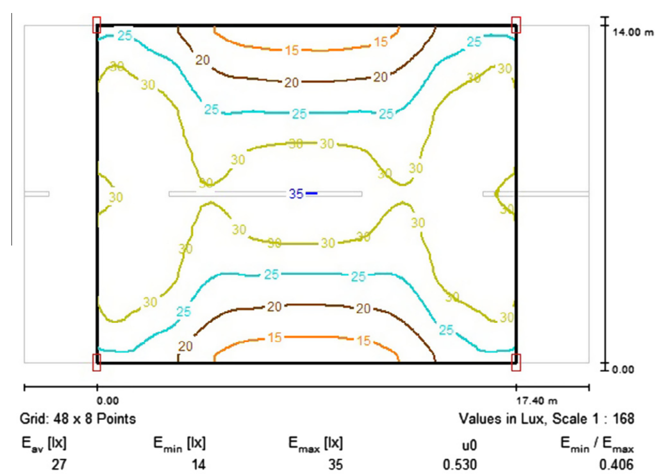

Fig. 14. Simulation result obtained with DIALux in the case of a two-sided coupled installation. The parameters of the design are, 8.2 m mounting height and 17.4 m spacing between luminaires in a street with 14 m width.

One-side configuration was ruled out because the ratio width-height is outside its corresponding range according to Table 4, despite previously being the most efficient solution (SE = 0.017 W/lux/m^2), nevertheless, as we can see in Fig. 15, the simulation shows values (E_{av} = 14 lux and U_0 = 0.24) lower than recommended ($E_{av} \geqslant$ 20 lux, $U_0 \geqslant$ 0.4).

As can be observed, the results of the chosen solutions, as evidenced by the simulations, they are in consonance with the recommended lighting levels (see Table 1). Since the calculation method is based on optimal solutions in terms of energy efficiency, it ensures the design of public lighting with an optimal and efficient luminaire arrangement (luminaire spacing, height, and distribu-

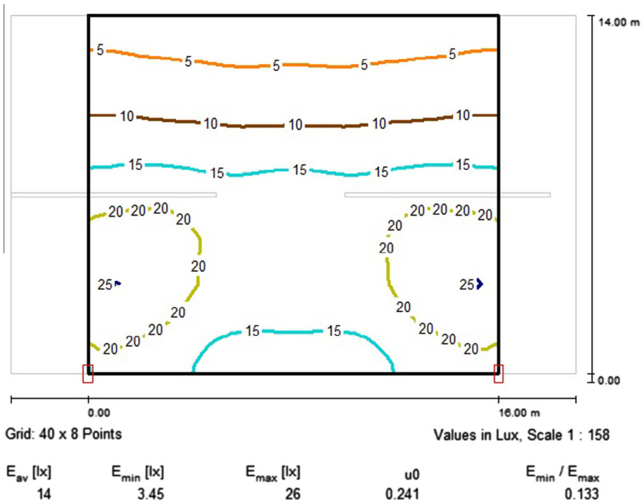

Fig. 15. Simulation result obtained with DIALux in the case of a one-sided coupled installation. The parameters of the design are, 9.4 m mounting height and 16 m spacing between luminaires in a street with 14 m width.

tion). Evidently, if the installation requires an even higher level of energy efficiency, this method can be used with another luminaire to obtain a new design without the use of simulation software programs. All that is necessary are the parameters (*a, b, c* and *d*) of the new luminaire, provided by the manufacturer to find the most energy efficient design for the new installation.

In summary, the method follows the following steps:

1. Calculation of spacing of luminaires *S* and mounting height *H*, applying Eq. (1) according to the street lighting class (or average illuminance recommended), with *a*, *b*, *c*, and *d* parameters provided by the manufacturer of the luminaire.
2. Calculation of street width and mounting height ratio in order to decide the configuration (one-sided, two-sided staggered or two-sided coupled).
3. In case of having one solution the procedure has finished. Otherwise, we choose the most efficient solution.

5. Conclusions

The target of this research has been to present one extremely quick and easy method for a quick planning of lighting installations which, in addition, guarantees maximum efficiency and let the designer choose the uniformity. This method is so easy that even one technician not expert in lighting can quickly plan the arrangement of luminaries, which could be really useful in emergency situations such a natural disasters. In addition, we pretend to highlight the power of NSGA-II, whose utility and versatility is proved in such applied fields of lighting technology, which hopefully will foster the use of these methods in other fields of engineering.

Finally, other conclusions can also be derived from this study:

1. The relationships obtained in this research are a quick, inexpensive, and reliable method that can be used to calculate the main parameters of any public lighting installation without the use of computer tools.
2. Such relationships, which are different for each type of luminaire and arrangement, should be included by the manufacturers in the datasheet of each model so that the clients can optimally plan the installation.
3. The current financial crisis, which has dramatically reduced the budget for all kinds of infrastructure, and particularly for public lighting all over the world, is a context that requires manufacturers and governments to find creative and inexpensive solutions for the design of lighting installations. In this sense, the proposed model is an excellent cost-effective tool that not only saves money but also contributes to sustainable public lighting.
4. In future work, this method will be extended and applied to other spaces, such as tunnel or indoor lighting.

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