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Optimal Selection of Distribution, Power, and Type of Luminaires for Street Lighting Designs Using Multi-Criteria Decision Model

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Abstract: This article introduces an innovative design method for public lighting systems that surpasses the limitations of conventional approaches, which rely on predefined lamp characteristics and spatial arrangements. By employing a linear additive model to solve a multi-criteria decision model, our study proposes an optimal design methodology considering several key aspects, including the distance between lamps, their type, power, and light distribution. The goal is to achieve optimal illumination that enhances visibility on public roads for drivers and pedestrians while simultaneously minimizing glare and installation costs and maximizing energy efficiency. The proposed methodology is implemented through an algorithm developed in MATLAB R2023b, with results validated through simulations in DIALux evo 12.0. This information is used to construct a decision matrix, assessed using the CRITIC method across 180 different scenarios within a specific case study. The findings demonstrate the effectiveness of multi-criteria decision-making as a tool for significantly improving the planning and design of lighting in public illumination systems, allowing for selecting the optimal combination of parameters that ensure the best lighting conditions.

Keywords: public lighting; multi-criteria decision; CRITIC method; optimization

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1. Introduction

A lighting system provides an artificial light source to facilitate the performance of daily activities in the absence of natural light sources or when their influence on the workspace is minimal [1]. The utility of these systems is commonly defined by the illumination level (E), which determines the light intensity on the work plane. Therefore, the design of lighting systems is based on determining the number of lamps and their distribution in the workspace to achieve the required illumination level, a procedure known as the lumen method [2,3].

When discussing street lighting, the performance of a lighting system is measured in terms of illumination level but also must take into account factors that affect comfort and functionality for the user [4–6]. The illumination level must be ensured at the eye level of pedestrians as well as at the sight level of drivers. It is important to maintain visibility across the entire path and prevent the lamp from dazzling people's vision. Adequate lighting levels reduce crime rates by allowing pedestrians to be aware of what is going on around them and reduce the possibility of a criminal hiding or having the alternative of being lost from sight during a chase. Therefore, illumination uniformity (Uo) and glare index (UGR) are included as performance parameters of lighting [7,8].

Another factor currently considered is energy efficiency. Street lighting is widely used both night and day to enhance visibility in areas with little to no natural light. Since artificial light sources that consume electrical energy are used, they can account for 21% to 40% of energy consumption in buildings in developing countries and up to 15% in industrialized countries [9,10]. This mode of operation also affects the cost of operation and maintenance, which is covered by public administration and can amount to a significant value [11,12].

It can be observed that the design of lighting requires meeting various criteria to ensure utility, comfort, and feasibility, making it not only a technical issue but also an economic one [13–15]. These issues can be analyzed by applying multi-criteria mathematical models or using heuristic algorithms; the difference between them is that the first strategy allows for an exact solution, while the second yields an approximate solution. Moreover, by using multi-criteria models, the influence of each criterion on the design can be evaluated, allowing for the inclusion of optimization [16].

Currently, research has been conducted where multi-criteria models are applied to the design of street lighting systems, tunnels, and indoor spaces, as developed by [9,12,17–19]. include multi-criteria models implemented for the problem, while the use of genetic algorithms is explored in the works of [5,15,20–22]. These studies differ in their optimization objectives and the number of criteria considered. Figure 1 summarizes these studies' basic information, identifying the issue's current state. Most studies use multi-criteria models with various techniques for solving or simplifying their resolution. Each project has its own optimization function, but largely they coincide in improving energy efficiency. All lighting projects comply with constraints related to the level and uniformity of illumination; some consider electrical power in the cost calculation, while others incorporate user feedback.

Verified Literature	Strategy		Optimization Approach			Restrictions			
	Multi-Criteria Model	Heuristic Algoritms	Installation and Operating Cost	Energy Efficiency	Lighting Comfort	Lighting Level and Uniformity	Glare	Lamp Power	User's Opinion
Li, Thou and Zou. 2021	x		x			x			
Rabaza et al. 2020		x		x		x			
Mandal et al. 2019		x		x		x	x		
Madias et al. 2021	x			x		x		x	
Beccali et al. 2019	x			x	x	x			x
Villa and Labayrade. 2013	x				x	x			x
Carli, Dotoli and Pellegrino. 2018	x			x		x			
Mattoni, Gori and Bisegna. 2017		x			x	x	x		
Zou and Li. 2010		x			x	x			
Qu et al. 2021	x		x			x			
This Article	x		x	x	x	x	x	x	

Figure 1. Comparative table of similar works [9,12,13,15,17–22].

This article presents an optimized public lighting design method using a multi-criteria decision model. It optimizes the spacing of lamps, type, power, and distribution based on the criteria of illumination level, light dispersion, glare, installation costs, and energy efficiency. Unlike other works, this design includes the effect of pavement type, and the costs include the effect of the lamps' lifespan. Finally, a linear additive model is used with the CRITIC method to define criteria weights and normalize the decision matrix. Unlike the similar works shown in Figure 1, this paper has the largest number of constraints and optimization criteria, representing a more generalized model of street lighting. In addition, the pavement effect on the light reflection is considered by the reflectance coefficient, which is not taken into account in most similar work.

1.1. Public Lighting Design Procedure

The design of street lighting consists of having an adequate level of illuminance on a working plane that considers visibility for drivers as well as for pedestrians; this is achieved by means of lamps suspended on poles along the street. Then, the design consists of determining the location of the lamp (h and s) and the spacing along the street (D), according to the scheme shown in Figure 2 below.

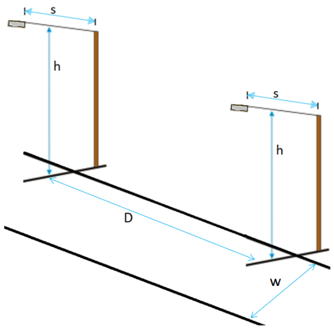

Figure 2. Variables involved in public lighting.

1.1.1. Determination of h and s

Mounting height (h) is employed to control glare, such that a greater height results in a lower glare effect, thereby enhancing visibility by moving the light fixtures away from the normal line of sight. Additionally, height aids in determining the luminous performance and the distribution of light from the fixture. Regulations have standardized height based on the maximum intensity of the lamp, as seen in Table 1. This standardization also facilitates the construction of poles on which they are mounted, although height can be increased if needed to improve uniformity.

Table 1. Minimum mounting height, m.

Maximum Intensity (*cd*)	Cut-Off Luminaire	Semi Cut-Off Luminaire	Non Cut-Off Luminaire
Up to 1000	6	6	6
From 1000 to 2000	7.5	7.5	7.5
From 2000 to 4500	7.5	7.5	-
From 4500 to 6000	7.5	7.5	-
Over 6000	9	9	-

Adapted from [23].

For the overhang (s), one condition is that it must not exceed one-fourth of the mounting height or one-fourth of the roadway width, leading to the establishment of Equation (1).

$$s = max\{h/4; w/4\} \tag{1}$$

1.1.2. Determination of D

The calculation is performed based on the total light output of the lamps and the average illuminance required. These terms are related by Equation (2), as expressed in [24]:

$$D = \frac{b \times M}{E_{av} \times W} \times U, \tag{2}$$

where D is the spacing between adjacent lamps in m; b represents light output of the lamp in lx; M corresponds to the maintenance factor, where a value of 0.85 is commonly used; E_{av} is the maintained average illuminance in Lm; W is used for the width of the roadway; and U is the utilization factor.

The value b depends on the lamp type used in the design and is a specification provided by the manufacturer; U is quantified based on the lamp's type and location, with standardized values determined by the ratio of the transverse distance to the mounting height [24]. The value of E_{av} is determined using Equation (3) as follows:

$$E_{av} = L_{av} \times F_{E/L}, \quad (3)$$

where L_{av} represents the average luminance required on the roadway in cd/m^2, and $F_{E/L}$ is the illumination to luminance ratio in $\frac{\text{lx}}{\text{cd/m}^2}$.

The value of L_{av} is standardized according to the classification of roads based on their usage. For this work, the values established in [24] have been considered, as they align with other international standards, such as [23,25], design manuals like [26], and are used in the works of [3–5,11]. Table 2 presents the values for roads considered as major routes, classified as Group A, which have been taken into account for this work.

Table 2. Recommended values for public lighting.

Group	Type of Road	L_{av} (cd/m^2)
A1	Highways. Speed limit over 70 km/h.	1.5
A2	Major roads (arterials). Speed limit from 55 to 70 km/h.	1.0
A3	Direct routes through urban areas. Speed limit 55 km/h.	0.75
A4	Link roads connecting direct routes with suburban roads.	0.5

Adapted from [23].

$F_{E/L}$ responds to the light distribution capacity of a luminaire and the type of surface to be illuminated, defining the values shown in Table 3. For Group A roads, the use of cut-off lamps is recommended, so only the first row would be considered, highlighting the need to predefine the type of surface considered in the design, namely, the type of pavement of the street to be illuminated.

Table 3. Conversion of luminance to illumination, $F_{E/L}(\frac{\text{lx}}{\text{cd/m}^2})$.

Type of Luminaire	Dark Surface	Medium Surface	Light Surface
Cut-off (C)	24	18	12
Semi-cut-off (SC)	18	13	9
Non-cut-off (NC)	15	10	7

Adapted from [23].

The utilization factor (U) can be selected based on the ratio $\frac{w-s}{h}$ and the wattage of the lamp being used, as [23] provides tables from which the value can be chosen. Once D value is calculated, the lighting distribution is evaluated such that the calculated value is used for unilateral and opposite bilateral cases, whereas for staggered bilateral, D is doubled, as illustrated in Figure 3.

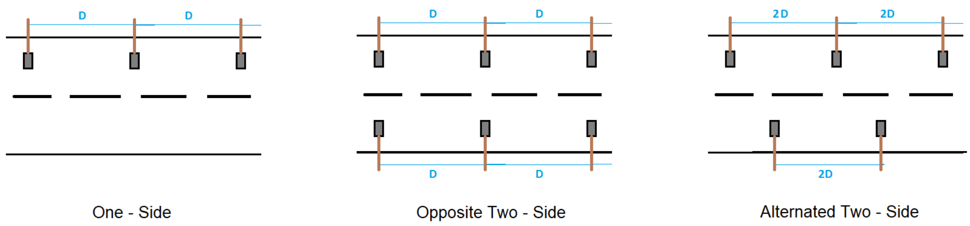

Figure 3. Distribution of public lighting.

2. Materials and Methods

To evaluate the application of multi-criteria decision-making in the design of public lighting systems, this study focuses on a two-lane public road without a median, each lane being 13.5 m wide, with a total length of 2 km. The maximum speed on the road is 50 km/h, categorizing it as group A2. Decision variables identified include the type of pavement, type of lamp, lamp wattage, and lighting distribution, with their values and relationships schematically represented in Figure 4, where the connections between variables are shown resulting in 180 scenarios.

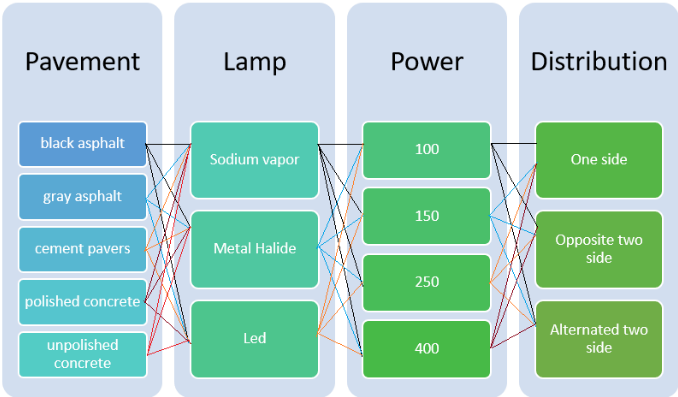

Figure 4. Design variables and their relationship.

Regarding the criteria, parameters that define the quality of illumination as well as the economic aspect of the design have been considered, including average luminance, uniformity, uniformity index, surface-sensation ratio, vertical illuminance, efficiency, installation cost, and operating cost. The values of the lighting quality parameters will be determined by simulation, thus eliminating the need to define an objective function, while for the economic parameters, the objective functions are defined in Equations (4) and (5) as follows:

$$C_{ins} = N_{lamp} \times (P_{lamp} + ((P_{ins}/6) \times h)) \quad (4)$$

$$C_{op} = N_{lamp} \times (P_{kWh} \times Pt_{kW} \times 12 \times 365/Ef) + N_{lamp} \times (P_{lamp}/VU_{lamp}), \quad (5)$$

where C_{ins} means installation cost of the design; C_{op} is the operation and maintenance cost; N_{lamp} is the number of lamps; P_{lamp} corresponds to unit price of a lamp; P_{ins} is assigned for installation price per lamp on a 6 m pole; h represents the height of the pole for the lamp; P_{kWh} is the price of electrical energy consumption per kWh; Pt_{kW} refers to lamp power in kW; Ef is the lamp efficiencyl and VU_{lamp} is assigned for the lifespan of a lamp.

2.1. Public Lighting Design

For each scenario, the procedure described in Section 1.1 is applied, determining the mounting height, overhang, and spacing between lamps for each scenario. In this study, the effect of the pavement type is included, as the reflection of light emitted by the lamps varies depending on the material. This can be quantified using the reflection coefficient with Equation (6) and the values from Table 4 as follows:

$$E'_{av} = E_{av} \times Cr, \quad (6)$$

where E_{av} means maintained average illuminance in Lm, and Cr is the reflection coefficient. Cr values correspond to those established in public lighting design regulations, which commonly are not used in the design since standard luminance values are already established according to the use of the road to be illuminated; however, this factor may determine scenarios for the construction of roads with a better street lighting system.

Table 4. Reflection coefficient.

Type of Pavement	Black Asphalt	Gray Asphalt	Cement Cob-blestones	Polished Concrete	Unpolished Concrete
Cr	0.1	0.2	0.35	0.5	0.4

The design is carried out through an algorithm developed in MATLAB, the flowchart of which can be seen in Figure 5. The algorithm relies on nested loops that facilitate the selection of different values for each variable and define indicators for selecting parameters and conducting the required iterative calculations; the program's output is a matrix that indicates the values of D, h, and s for each scenario.

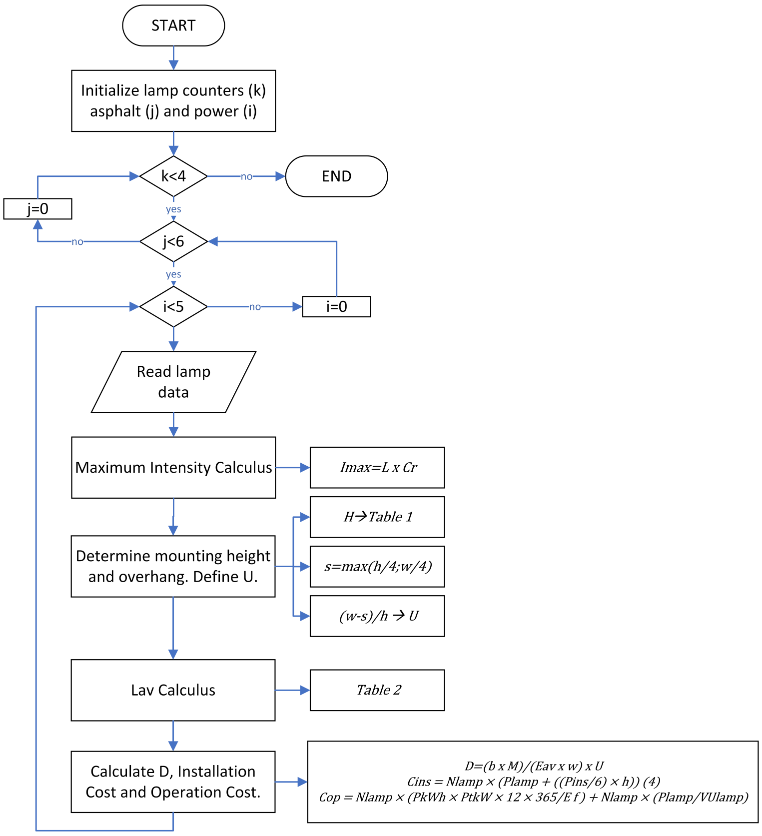

Figure 5. Flowchart for public lighting design.

2.2. *Public Lighting Simulation*

To obtain the lighting criteria for each scenario, simulations are performed using the DIALux evo 12.0 software. Figure 6 shows the software's workspace views; in the "Road" tab, the characteristics of the road to be simulated are defined, with the road surface parameter Q0 used to set the reflection coefficient, and the classification of the road is selected in the validation field. The lamp and its distribution are chosen in the "Luminaire Selection" tab, and the values of D, h, and s are entered. The results are graphically presented through isolux curves on the road model, and the numerical results are in a table.

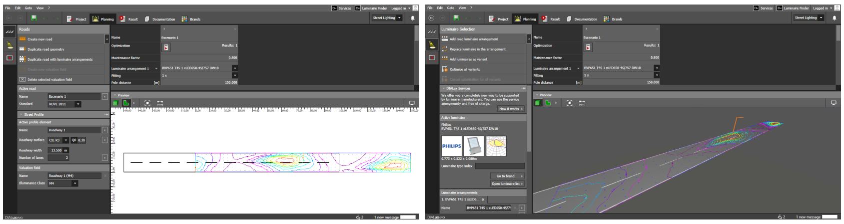

Figure 6. Working windows in DIALux Evo.

2.3. Multi-Criteria Analysis

Multi-criteria decision-making methods enable the ranking of alternatives in problems where a decision depends on multiple criteria, ensuring that the decision is explicit, rational, and efficient. The method establishes a mathematical optimization model with a set of criteria or objective functions F defined by Equation (7), where X is a set of variables defined by Equation (8), whose combination of elements defines the set of scenarios defined by the set A in Equation (9) [27–30] as follows:

$$F(X) = [F_1(X), F_2(X) \ldots, F_n(X)] \tag{7}$$

$$X = [x_1, x_2 \ldots, x_m] \tag{8}$$

$$A(X) = [A_1(X), A_2(X) \ldots, A_i(X)], \tag{9}$$

where $A_i(X)$ is the element representing the ith combination among the elements of X. For each element of A, every element of F is evaluated in the respective combination of elements of X, and the obtained results are organized in a matrix known as the decision matrix, as shown in Equation (10).

$$D = \begin{bmatrix} F_1(A_1) & F_1(A_2) & F_1(A_3) & \ldots & F_1(A_i) \\ F_2(A_1) & F_2(A_2) & F_2(A_3) & \ldots & F_2(A_i) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ F_n(A_1) & F_n(A_2) & F_n(A_3) & \ldots & F_n(A_i) \end{bmatrix} \tag{10}$$

Multi-criteria analysis methods can be classified according to the way that they work with the decision matrix data, highlighting the following [31–33]:

Direct analysis of the performance matrix. Determines the criteria dominance, when these allow to clearly determine one scenario more favorable than another, allowing criteria elimination and defining similarities and differences between dominants to simplify the decision making task.

Multi-attribute utility theory. It establishes a procedure to determine the independence between criteria and determines mathematical function parameters to calculate an index U, which determines the scenario performance. The method complexity lies in the definition of the mathematical function, which requires knowledge and expertise in the evaluated process.

Linear additive model. It can be used when there is no relationship between the criteria, and if uncertainty is not included in the multi-criteria model, defining a linear model where the scenario performance is determined by multiplying the matrix values by an importance factor for each criterion and then summing all the results.

The analytical hierarchy process. Defines a standard linear additive model and establishes a procedure for determining the criteria importance factor based on criteria and scenario pairwise comparisons by asking questions about the importance of one criterion over another.

From the decision matrix, the decision vector P is obtained, whose values result from the weighted sum of the values for each scenario, utilizing Equation (12). The weights of the criteria W_n are determined through statistical techniques, and the highest value in the set P indicates the optimal scenario for the multi-criteria problem.

$$P_i = \sum_{p=1}^{i} \sum_{q=1}^{n} (W_q \times D_{pq}) \tag{11}$$

$$A_{opt} = max\{P\} \tag{12}$$

For this article, the decision matrix is formed with the results obtained in Sections 2.1 and 2.2, obtaining a matrix of 8 × 180. To determine the optimal scenario, the CRITIC method is used to calculate the weights of each criterion (w_j) using Equations (13)–(15); this method uses the variance of each criterion (σ_j) and its correlation (r_{jk}). The matrix values are updated using Equation (13) [34,35].

$$w_j = \sigma_j * \sum_{k=1}^{n} (1 - r_{jk}) \tag{13}$$

$$r_{jk} = \frac{cov(j,k)}{\sigma_j * \sigma_k} \tag{14}$$

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} (x_{ij} - (\sum_{i=1}^{m} (x_{jk})/m))^2}{m-1}} \tag{15}$$

$$m_{ij} = \frac{x_{ij} - xmin_{ij}}{xmax_{ij} - xmin_{ij}} \tag{16}$$

$$m_{ij} = \frac{xmax_{ij} - x_{ij}}{xmax_{ij} - xmin_{ij}} \tag{17}$$

Before calculating the weights, it is necessary to normalize the values of the decision matrix. For this, range normalization is used, which considers the minimum and maximum values, defining Equations (16) and (17) for a benefit or cost criterion, respectively. This process is carried out through an algorithm in MATLAB, whose flowchart can be seen in Figure 7, which takes the decision matrix as input, determines the minimum and maximum for each criterion, normalizes them, calculates the weight for each variable, and finally returns the normalized matrix and the decision vector, identifying the maximum.

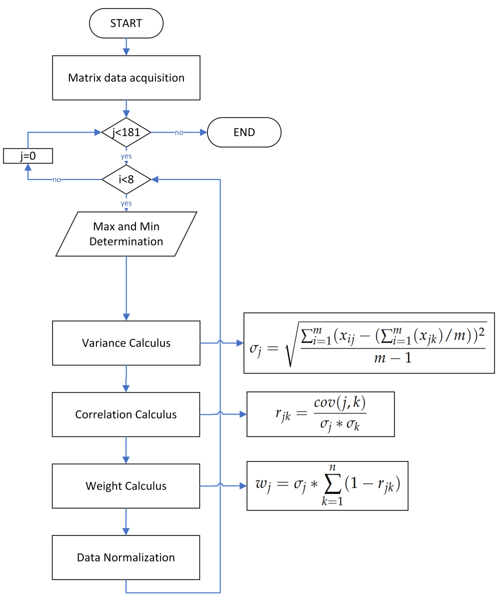

Figure 7. CRITIC flow chart.

3. Results

According to the procedure explained in Section 2.1, the MATLAB algorithm is executed with the data of the proposed street in Section 2; for each scenario, the data shown in Table 5 are obtained. For example, the results obtained for three scenarios are shown, where sodium vapor lamps of 100 W are used on the street with black asphalt, and the arrangement of the lamps along the street is changed. This allows for clearly identifying the scenario's variable combination and the values obtained for the calculable criteria. The data are obtained for all 180 scenarios where LED and metal-halide lamps are used, thus defining the decision matrix.

Table 5. Results of public lighting during design.

Variables/Criterion	Scenario 1	Scenario 2	Scenario 3
Lamp Type	Sodium vapor	Sodium vapor	Sodium vapor
Power (W)	100	100	100
Pavement	Black asphalt	Black asphalt	Black asphalt
Height (m)	6	6	6
Protrusion (m)	3.4	3.4	3.4
Arrangement	Unilateral	Alternating Bilateral	Opposite Bilateral
Spacing (m)	17	34	17
Lamps	119	238	238
Efficiency	80	80	80
Installation	5572.77	11,145.54	11,145.54
Operation	59,941,585	119,883,171	119,883,171

With this information, the simulation of each scenario is carried out to obtain the quality parameters of public lighting, as explained in Section 2.2. In Figure 8, the results from DIALux are shown, along with the three-dimensional view displaying the isolux curves and the arrangement of the lamps. For each simulation, it was ensured that the parameters met the minimum standards set in [25]. Regarding illumination, the design process consistently yielded good parameters; in some scenarios, adjustments were made only to the lamp height.

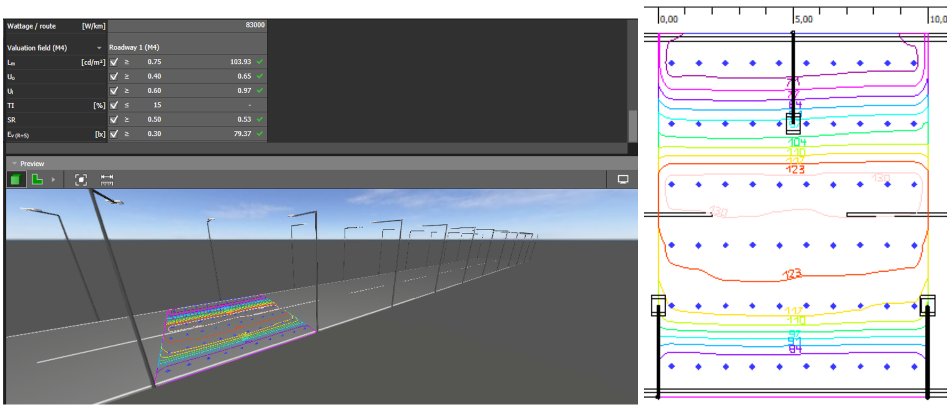

Figure 8. Results obtained with DIALux.

Quality lighting parameters were added to Table 5 to complete the decision matrix. In Table 6, the decision matrix for the first three scenarios is shown, including only the values corresponding to the criteria, which are the ones influencing the multi-criteria algorithm.

Table 6. Results of public lighting design including simulation results.

Criterion	Scenario 1	Scenario 2	Scenario 3
Efficiency	80	80	80
Installation	5572.77	11,145.54	11,145.54
Operation	59,941,585	119,883,171	119,883,171
Lm	1.86	1.93	3.87
Uo	0.18	0.19	0.33
Ui	0.76	0.42	0.78
SR	0.3	0.31	0.3
Ev	0.51	0.6	1.37

To this decision matrix, the CRITIC method is applied. Firstly, the values are normalized, wherein it is defined that installation and operation criteria are of a cost nature, while all others are of a benefit nature. Thus, the optimal scenario corresponds to the maximum of the weighted sums. The normalized data of the eight criteria for the 180 scenarios can be observed in Figure 9, which facilitates the visualization of the decision matrix. It can be seen that there is no uniform pattern of behavior in the obtained data, and it can be observed that, with respect to the SR criterion, there is a certain stability of values in all scenarios as well as in C_{ins}. This implies that the criteria will have less importance in the decision, as they do not allow us to identify a difference between scenarios. It is also noticeable from scenario 100 that the values begin to rise for each criterion, indicating that the scenario's characteristics tend to improve the street lighting design.

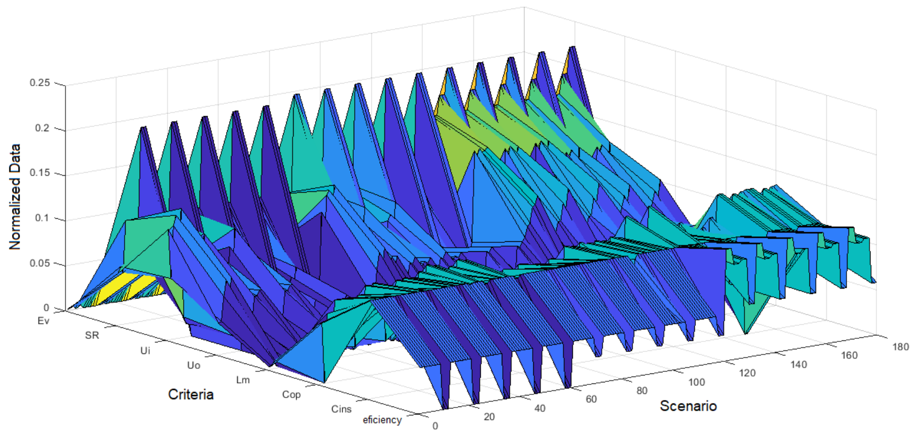

Figure 9. Graphical representation of the normalized decision matrix.

The optimal scenario corresponds to the one with the best conditions regarding all criteria, i.e., the one with the highest weighted sum value. As observed in Figure 10, where the result of the weighted sum is presented as the cumulative effect value of all criteria over the lighting design, the best scenarios correspond to those with LED lamps of 150 W, installed at a height of 7.5 m, with a protrusion of 3.4 m in a bilateral opposite disposition. The highest among all stands out for having pavement made of cement pavers. These results strengthen the trend of transitioning to LED lamps, not only for efficiency and environmental contribution but also because they collectively represent the best option for public lighting.

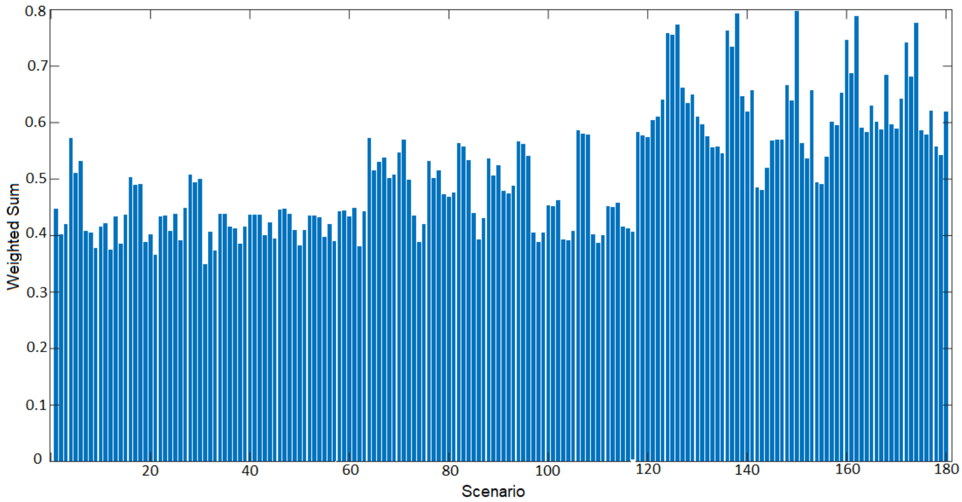

Figure 10. Weighted sum results.

Next, the best scenario is analyzed with respect to a single criterion, considering the average luminance. According to Figure 11, the best scenario is number 168, which entails 400 W LED lamps installed at a height of 7.5 m, with a protrusion of 3.4 m in a bilateral opposite disposition and polished concrete pavement. Regarding this criterion, scenario 150 ranks second.

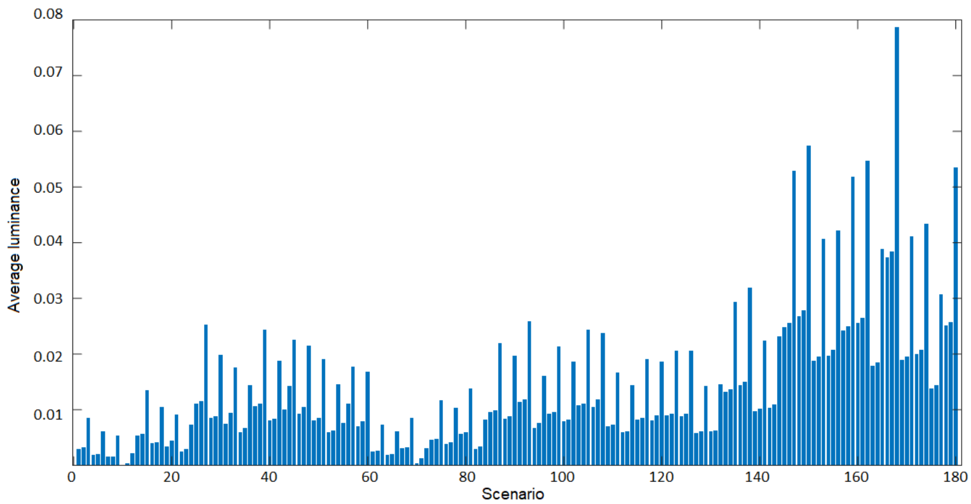

Figure 11. Illuminance results (Lm).

In Figure 12, the results regarding illuminance uniformity are presented. The best scenario is number 138, which involves using 150 W LED lamps installed at the height of 6 m, with a protrusion of 3.4 m in a bilateral opposite disposition and gray asphalt pavement. Regarding this criterion, scenario 150 once again ranks second.

In Figure 13, the results regarding the economic component, i.e., the installation and operation costs associated with the public lighting design, can be observed. It is found that the scenario with the lowest installation cost is number 148, where 150 W LED lamps are used at a height of 7.5 m in a unilateral disposition. Scenario 150 ranks 15th. Regarding this parameter, it can be noted that most scenarios have the same value because only the installation cost based on the pole height was considered, a value repeated in several designs.

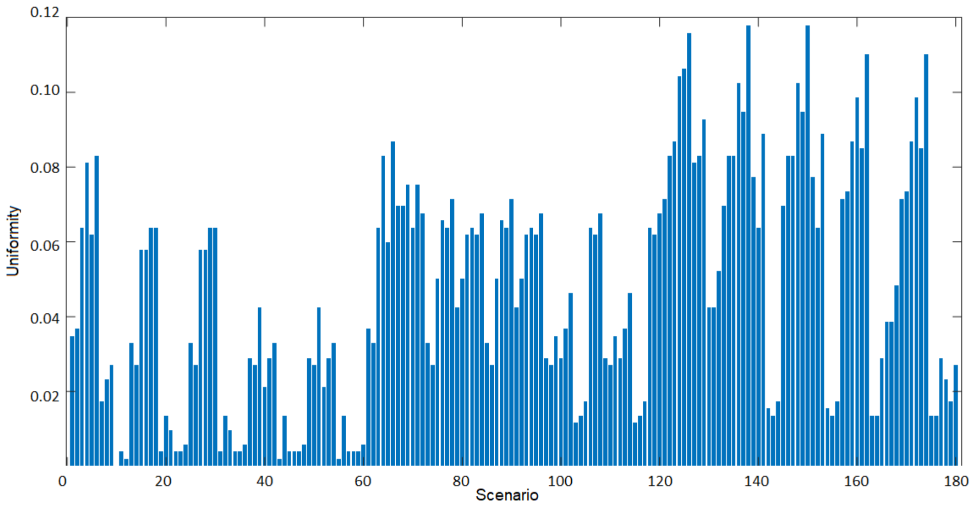

Figure 12. Economic component results (Uo).

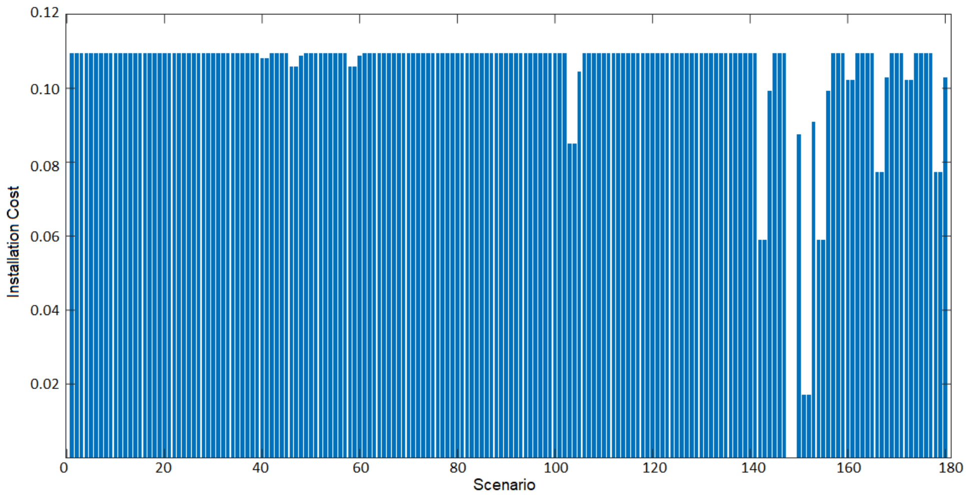

Figure 13. Installation cost results.

If only the operating cost is considered, as shown in Figure 14, scenario 3 has the lowest cost, while scenario 150 is ranked 26th. The analysis with respect to individual criteria further clarifies the conception of street lighting design as a multi-criteria analysis problem, where one must optimize according to different criteria to determine the best scenario.

This method of street lighting design can be extended to other types of lighting, such as ornamental lighting, widely used in parks or decoration of tourist sites, since the color of the light can be included as a variable and the color temperature as a criterion. These factors affect the details in plants and monuments, potentially highlighting a specific object, making it more visually appealing. Additionally, it could include the opinion of visitors, including methods of analyzing the decision matrix with qualitative factors.

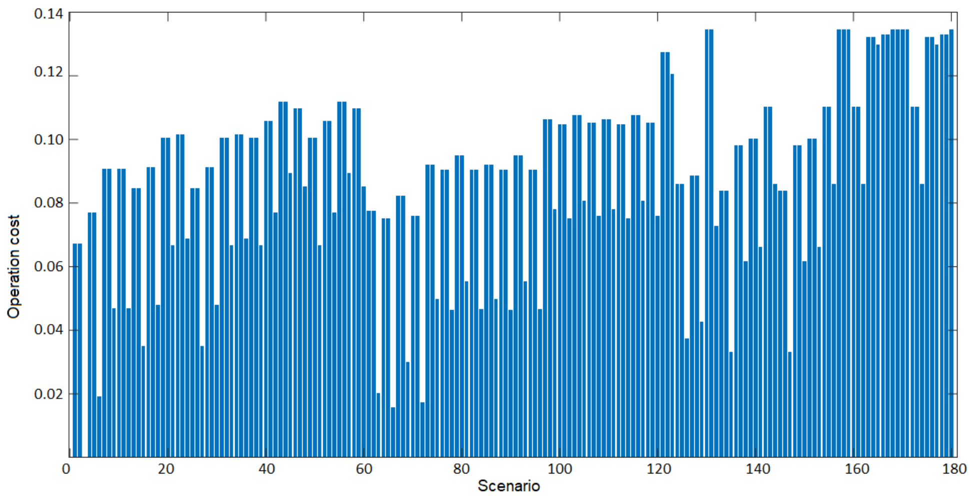

Figure 14. Operating cost results.

4. Conclusions

The design of street lighting should not only consider the average luminance level in the driver's plane of view as it was traditionally done, but should also consider all aspects that involve lighting and economic comfort. Therefore, it is necessary to adapt the traditional design strategies to a multi-criteria analysis and optimization approach, thus obtaining a more complete design.

A multi-criteria algorithm has been developed to design street lighting, obtaining a complete tool that can be used from the planning stage of a street because one of the variables involved is the type of pavement, so the material that leads to the optimal design can be chosen. The use of this variable is one of the aspects to highlight in this work because, according to the literature review, it has not been taken into account in most similar work, so a strategy is given to include it not only in the design but also in the validation by means of DIALux.

The validation of the designs made with the lumen or traditional method observed that the design always allows obtaining an adequate level of average luminance and uniformity within the regulations. However, it was necessary to adjust the installation height in several scenarios because there was glare, especially on surfaces with higher reflection coefficients. This aspect is very important to consider in scenarios where a type of pavement has already been predefined, since it is not convenient to choose high-power lamps or to install them at low heights.

The results obtained show that public lighting lamps should be preferable with LED technology, which not only implies a contribution to energy efficiency and, therefore, environmental contribution but also represents a favorable scenario, as they are the starting point towards the optimal operational and economical design, becoming the recommendation for new lighting projects or replacement in projects already installed.

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