Luminotechnical Calculation Algorithm for Public Lighting in VBA

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Public lighting is essential for urban quality of life and safety. With the advent of LED technology and increasing energy efficiency directives, its modernization has become increasingly important. This study developed a VBA algorithm to optimize the technological transition of public lighting, focusing on reducing simulation time and installed power. Using the lighting projects from Teresina/PI's Public-Private Partnership (PPP) as a reference, the algorithm was validated through comparisons with DIALux 4.13 software. The results demonstrated that the algorithm achieved a Mean Absolute Percentage Error (MAPE) below 8% for luminance and illuminance calculations, indicating high accuracy. Furthermore, it significantly reduced simulation time, completing 13,161 simulations in 37 hours, compared to 2,121 simulations in 140 hours using DIALux. These results highlight the algorithm's efficiency and effectiveness.

Keywords: Public Lighting. Energy Efficiency. Luminotechnical Simulation.

Public lighting (IP) is fundamental to urban quality of life, directly influencing safety, traffic flow, and nighttime activities. Although public lighting was adopted in Brazil as early as the 18th century, formal standardization only emerged in 1992 with the publication of ABNT NBR 5101.

This standard ensures efficient, safe, long-lasting lighting systems [1].

Brazil has over 18 million lighting points, which consume approximately 14.3 TWh—around 4.5% of the country's total electricity consumption. Most of these points rely on outdated technologies such as fluorescent, sodium vapor, and mercury vapor lamps, which are energy-inefficient and require extensive maintenance. In contrast, LED technology presents a more sustainable solution, offering energy savings of up to 85% compared to incandescent lamps and 65% compared to compact fluorescents. In addition, Public-Private Partnerships (PPPs) have emerged as a strategic model for modernizing public lighting systems, enabling municipalities to outsource their management while ensuring technical and financial viability [2].

The number of lighting simulations required for a given project varies depending on several factors, including the current conditions of each road and the adjustments needed to comply with applicable standards. A single street may demand multiple simulations due to sections with differing lighting characteristics. Furthermore, the quantity and variety of luminaires increase the number of required simulations. For bidding companies, testing a larger number of luminaires enhances the chances of identifying a lower-power option that still complies with standards—thereby reducing implementation costs and maximizing energy savings in PPP projects.

In this context, luminotechnical modeling using specialized software is essential in modernizing public lighting through PPPs. However, this process is often labor-intensive and time-consuming due to the large volume of required simulations and their inherent complexity. To address this challenge, this study presents a tool developed in Visual Basic for Applications (VBA) capable of conducting luminotechnical simulations based on Brazilian standards and public lighting characteristics. The primary objective is significantly reducing simulation time compared to commercially available software. To validate the tool's

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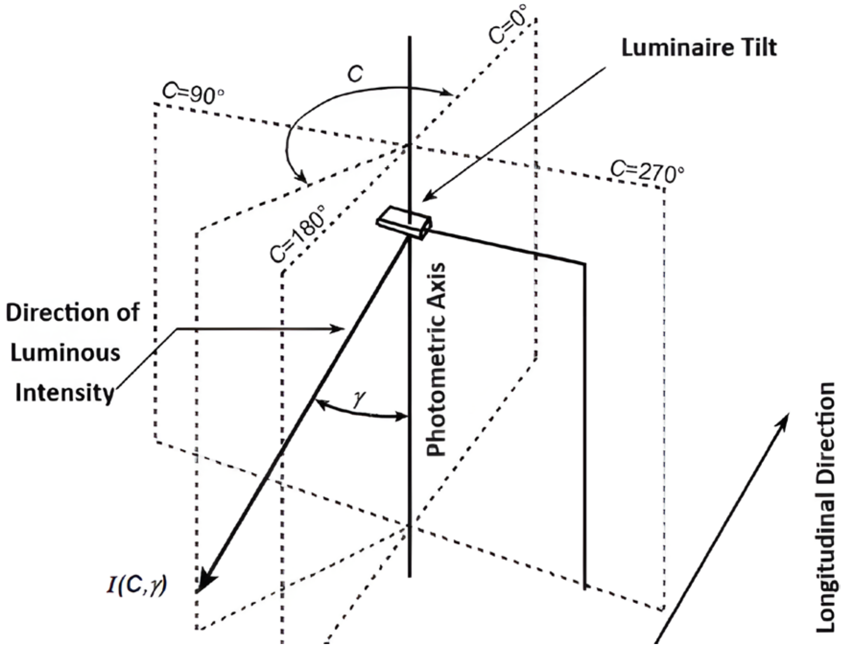
Figure 1. Luminous intensity as a function of angles C and γ [1].



accuracy, the Mean Absolute Percentage Error (MAPE) was employed to compare results for luminance and illuminance obtained using the proposed algorithm with those from DIALux 4.13 simulations [1].

Materials and Methods

The algorithm is based on the Technical Report Road Lighting Calculations CIE 140 - 2000, which defines the necessary variables and formulations to compute the luminotechnical parameters established by NBR 5101:2018 [1–3].

The coordinate system used for road lighting luminaires is typically the I (C,γ) system. This system defines the luminous intensity of a luminaire—usually provided by manufacturers in the IES (Illuminating Engineering Society) format—according to the IES LM-63-1991 standard. The luminous intensity is expressed in candelas per kilolumen (cd/KLM) for all light sources within the luminaire [4].

To determine the luminous intensity emitted by a luminaire toward a specific point on the road, the vertical photometric angle (γ) and the photometric azimuth angle (C) must be calculated. These angles define the light's trajectory from the luminaire to the target point, as illustrated in Figure 1. The calculations must account for the luminaire's orientation, tilt, and rotation in their application. Therefore, mathematical conventions are required to measure distances along the road and to rotate the luminaire around its axes.

Calculation Grid

To calculate the photometric angles C and γ, it is necessary to define the points at which the luminous intensity will be calculated. The calculation grid is established in the NBR 5101:2018 standard, which specifies the sizing and spacing of calculation points according to the characteristics of the road under study. The standard provides guidelines for defining these points on a road with three lanes and a specific spacing between poles [1].

Based on this standard, luminotechnical variables should be calculated at intervals of 6.25% of the spacing between poles along the length of the road, known as the longitudinal spacing. A new calculation line should also be created for every 20% fraction of the lane width, referred to as the transverse spacing.

The resulting calculation grid matrix consists of 17 columns of points evenly distributed along the longitudinal direction and five rows of points within each lane. The NBR 5101:2018 standard also specifies that the width of the road lanes should be considered between 2.7 and 3 meters [1].

Luminous Intensity

Luminous intensity values are determined based on the angles C and γ, which are provided in curves by manufacturers for luminotechnical studies. These curves are typically delivered in the IES (Illuminating Engineering Society) format, allowing for standardized data representation. To obtain the luminous intensity at a specific point, it is essential to calculate the angles C and γ. This calculation calculates the luminous intensity distribution influenced by each luminaire within the system [4].

Once the necessary adjustments are made, such as accounting for the spacing between poles, the installation height of the luminaires, and the coordinates within the rotated system (x', y', z'), the angles C and γ can be accurately calculated for each point, as shown as Figure 2.a. This step is critical in ensuring that the luminous intensity values reflect the actual lighting conditions on the ground, considering the geometric and spatial arrangements of the luminaires [1-3].

In cases where a luminous intensity value is required in a direction that falls between the measured directions in the I-Table, interpolation becomes necessary. The interpolation process involves calculating between the four nearest intensity values in the direction of the azimuth angle C and the elevation angle γ. Due to the lack of more robust statistical modules in Visual Basic, quadratic interpolation was chosen as the method for this task. This method involves interpolating three adjacent columns in the I-Table, allowing for determining intensity values in γ. The interpolation is then performed across the table to find the required value at the specific combination of (C, γ) [3].

Road surface reflection (R-table)

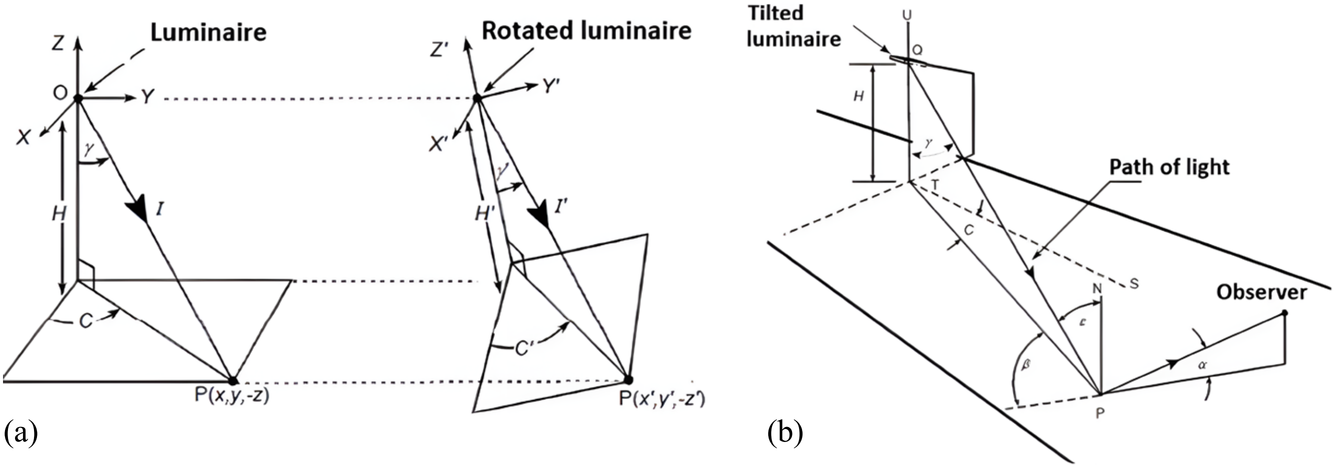
The R-table is a reference table containing data on the road surface's luminous reflection according to the angles β and ε. These data are conventionally expressed in terms of the luminance reduction coefficient multiplied by 10,000 [1]. The data in this table vary depending on the type of road surface, such as asphalt or sand. As illustrated in Figure 2.b, β is the complementary angle between the vertical plane through the luminaire at point Q and the observation point P and the vertical plane through the observer and point P. The angle α represents the angle between the observer's line of sight and the road surface, which is fixed at 1°.

The observer moves along the longitudinal centerline of the calculation grid for each lane. The angle ε is the incidence angle at point P, ST represents the longitudinal direction, Q is the photometric center of the luminaire, UQT is the vertical axis of the luminaire, and PN is normal to the surface.

When an R-value is required for tangent values of ε that fall between the data points in the R-table, quadratic interpolation must be used. This interpolation process requires three values from the R-table for each interpolated value. If an R-value is needed at a specific point (tan ε, β), the interpolation is first performed using three adjacent columns in the R-table that encompass the point. This allows for calculating three R values at the given tan ε. The interpolation is then carried out across the table to find the required value at the specific (tan ε, β) combination.

The R-table model used in this project is the R3, corresponding to the luminous reflection on asphalt-paved roads. The data in this table are consistent with the model used in the OpenEI algorithm. The initial goal was to use the same data utilized in the DIALux 4.13 software; however, the company responsible for developing the software does not disclose such information [5].

Figure 2. (a) Coordinate system with luminaire rotation. (b) Lighting scheme at a specific point on the road [1].



(a) (b)

2.6 Luminance, Illuminance, and Uniformities

Given the definitions of the calculation grid, I(C,γ), and R(β, tan ε.), we can define the variables that measure the lighting performance on the road. It is important to note that it is not necessary to calculate these variables at every point on the grid due to the influence of each luminaire. In the transverse direction, the calculation should encompass the entire width of the lane on roads without a central median and the width of a single lane on roads with a central median. [1 – 3]. So, luminance (L) measures the density of light intensity reflected in each direction, with the unit being candela per square meter. Considering the perimeter of influence of the luminaires, the luminance at each point is calculated by:

$$L = \frac{I(C,\gamma).R(\beta, tg\ \varepsilon).MF}{H^2.10000} \tag{1}$$

Where MF corresponds to the maintenance factor of the luminaire, L is the luminance at the calculated point. Additionally, horizontal illuminance was considered the method for calculating the illumination intensity (E), with the unit of measurement being lux (lx). The horizontal illuminance at a specific point is calculated by:

$$E_H = \sum \frac{I(C,\gamma).cos^3 \varepsilon.\Phi.MF}{H^2} \tag{2}$$

Where EH is the horizontal illuminance at the point, measured in lux; Φ is the initial luminous flux of the luminaires in kilolumens (klm).

The average illuminance and luminance are calculated as the arithmetic mean of the values obtained at the designated calculation points. The factors used to evaluate luminance distribution along the road include the global minimum uniformity (U_0) and the longitudinal uniformity (UL). Global minimum uniformity assesses the lowest luminance levels on the road by dividing the minimum luminance by the average luminance. In contrast, longitudinal uniformity reflects the consistency of luminance distribution along the calculation grid and is calculated by dividing the minimum luminance by the maximum luminance. Similarly, minimum illuminance uniformity (U) evaluates the lowest level across the road, calculated as the ratio of the minimum illuminance to the average illuminance.

Evaluation

A comparative analysis was conducted using DIALux 4.13, a widely adopted commercial lighting simulation software, to validate the algorithm's performance. The comparison maintained identical simulation parameters, and accuracy was evaluated using the Mean Absolute Percentage Error (MAPE) method. MAPE quantifies the percentage deviation between the algorithm's results and those obtained from DIALux, thereby providing an objective measure of accuracy for luminance, illuminance, and uniformity parameters as required by NBR 5101:2018.

Simulations were carried out for roads with one to four lanes, with lane widths varying from 3 to 12 meters. A depreciation factor of 0.8 was consistently applied across all simulations. Luminaire installation heights ranged from 7 to 10 meters, and tilt angles were incrementally adjusted by 5° up to a maximum of 15°, which aligns with standard recommendations.

Case Study

A case study was conducted using Teresina's public lighting concession, which involved modernizing 92,800 lighting points. The initiative focused on transitioning to LED technology to achieve substantial energy savings. The algorithm executed 13,161 simulations in only 37 hours, compared to 2,121 simulations in 140 hours using DIALux, demonstrating significantly higher computational efficiency.

Results and Discussion

The results of the accuracy evaluation were promising: the MAPE for illuminance (E) was 3.87%, for luminance (L) 3.63%, for illuminance uniformity (U) 5.96%, for global minimum uniformity (U_0) 9.22%, and for longitudinal uniformity (UL) 13.28%. However, longitudinal and global minimum uniformity values exhibited deviations beyond ideal thresholds. These discrepancies can be attributed primarily to differences in the road surface reflectance data (R-Table), significantly affecting luminance and uniformity calculations. The developed algorithm relies on a set of reflectance values that may not correspond precisely to those used in DIALux, as the latter's reflectance database is proprietary and not publicly disclosed. Consequently, discrepancies arise, particularly in parameters that depend on extreme luminance values.

Another contributing factor is the algorithm's interpolation method. Due to the limitations of the VBA platform, quadratic interpolation was used instead of more sophisticated techniques, which may have affected the precision of the luminance calculations.

In terms of efficiency, the algorithm consistently outperformed DIALux 4.13 across all road classes by achieving a lower average power per lighting point, as shown in Table 1. For instance, in V1-class roads, the algorithm reduced the average power per point by over 50W. When these savings are extrapolated across the complete set of road classes in the simulations, the algorithm's predicted reduced installed load following the technology transition was more substantial than that of DIALux—66% compared to 58%, translating to an additional 1.2 MW reduction.

Furthermore, under the Energy Bill Bonus (BCE) incentive, which allows financial benefits from energy savings exceeding a 50% efficiency target to be shared, the algorithm could yield approximately R$1,274,886.30 in additional annual profits for the concessionaire and R$318,722.32 for the municipality (Table 1).

Conclusion

The results demonstrated that the algorithm achieved a Mean Absolute Percentage Error (MAPE) of less than 5% for illuminance and luminance, while uniformity-related errors ranged from 5% to 14%. Regarding computational efficiency, the algorithm proved significantly superior, completing 13,161 simulations in just 37 hours—compared to only 2,121 simulations performed in approximately 140 hours by DIALux 4.13. In the case study involving the municipality of Teresina, the algorithm outperformed DIALux by proposing lighting solutions that achieved a 66% reduction in energy consumption—well above the 50% minimum requirement established by the municipality and the 58% reduction achieved by DIALux. This additional energy savings translates into approximately R$ 1.3 million in annual

Table 1. Calculation basis for the expected load reduction comparison.

Municipality		**Algorithm**		**DIALux 4.13**	
Lighting class	**Quantity of Luminaires**	**Medium Power per Luminares (W)**	**% of Savings**	**Medium Power per Luminares (W)**	**% of Savings**
V1	7,401	111,9	75	166,7	63
V2	5,709	90,5	67	116,4	58
V3	8,233	75,1	65	87,5	60
V4	15,122	40,6	76	55,0	68
V5	56,335	34,5	62	40,3	55
TOTAL	92,800	48,71	66	61,65	58

revenue for the concessionaire, thus improving the public lighting project's technical and financial viability.

For future research, it is recommended that alternatives be explored to reduce computational errors in various parameters further. One potential avenue is adopting more versatile programming languages, such as Python, allowing advanced interpolation techniques beyond quadratic interpolation. Moreover, integrating machine learning strategies, such as the Extreme Learning Machine (ELM) in a hybrid grey-box modeling approach, could further minimize discrepancies—particularly those arising from limitations in R-table data [6].

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