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Maintenance Factor Identification in Outdoor Lighting Installations Using Simulation and Optimization Techniques

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Received: 20 July 2018; Accepted: 14 August 2018; Published: 20 August 2018

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Abstract: This document addresses the development of a novel methodology to identify the actual maintenance factor of the luminaires of an outdoor lighting installation in order to assess their lighting performance. The method is based on the combined use of Radiance, a free and open-source tool, for the modeling and simulation of lighting scenes, and GenOpt, a generic optimization program, for the calibration of the model. The application of this methodology allows the quantification of the deterioration of the road lighting system and the identification of luminaires that show irregularities in their operation. Values lower than 9% for the error confirm that this research can contribute to the management of street lighting by assessing real road conditions.

Keywords: artificial lighting; simulation; calibration; radiance; GenOpt; street light points

1. Introduction

Artificial lighting accounts for 19% of the worldwide electricity consumption [1]. There is substantial potential for savings in electricity-related costs because inefficient light sources continue to be used all over the world [1,2]. The International Energy Agency (IEA) [3] and the European Union (EU) have developed ambitious and wide-ranging energy policies and strategies for the future. The 2030 climate and energy framework of the EU establishes three key targets aimed at achieving a safer, more competitive, and more sustainable energy system. They are looking for: (i) at least 40% reduction in greenhouse gas (GHG) emissions since 1990, (ii) at least 27% of total energy consumed to be renewable energy and (iii) at least 27% enhancement in energy efficiency [4,5]. With regard to these energy reduction strategies, lighting can play a fundamental role because of it offers considerable potential for improvement. The Lighting Europe's Strategy Roadmap 2025 focuses efforts on profitable approaches such as LEDification, intelligent lighting systems, human-centric lighting and circular economy [6]. Different types of lamps such as incandescent lamps, halogen lamps, fluorescent lamps and Light Emitting Diodes (LEDs) are used in artificial lighting. Montoya et al. [7] analyzed the indoor lighting techniques used throughout history and its impact on energy saving and sustainability coming across that the recent advances are significant to improve the people's living conditions. LED technology is highlighted because of its huge potential to reduce energy consumption and its fast evolution to high performance energy transformation [2,5,8,9].

Indoor building lighting has been deeply studied [10–13], but this work is focused on outdoor lighting. Currently, street and road lighting facilities are one of the highest energy consumers owing to their inefficiency. They account for up to 2.3% of the global electricity consumption [14,15]. Moreover, high-quality outdoor lighting is an essential service for a city; it has economic benefits for municipalities, engenders a feeling of safety for inhabitants, aids the vision of drivers and pedestrians and contributes to energy efficiency [14,16,17]. Therefore, lighting optimization is an important field of study in modern society and several authors have carried out extensive research on this issue [2,14,16–19]. Nardelli et al. [2] evaluated the potential of LED technology and their results showed that LED light sources have an extensive lifecycle, good luminous efficiency and superior color rendering index, although the acquisition costs are still high. Yoomak et al. [16] assessed in-depth the performance of LED technology for roadway lighting applications. These authors simulated roadway lighting quality and then set an experimental scenario to evaluate the energy saving, making some conclusions regarding the benefits of LED luminaires. Other authors have evaluated the influence of lighting in obstacle detection, demonstrating that positioning has a strong influence at low illuminances, e.g., a hub-mounted lamp improved detection compared to a handlebar-mounted lamp [18]. Gago-Calderón et al. [17] studied LED photometric properties such as illuminance, uniformity, disability and discomfort glares and enhanced these properties by using an improved optic cover. Corte-Valiente et al. [14] presented a new algorithm to optimize street lighting installations by obtaining the overall illuminance uniformity. They found that the Levenberg–Marquardt back-propagation algorithm was the best at minimizing the error. Di Mascio et al. [19] studied the influence of the type of road pavement on maintenance costs of the lighting system in a tunnel, concluding that the required levels of illuminance are lower for concrete pavements to guarantee the same luminance values to offer the same luminance.

All these studies revealed the importance of lighting optimization in reducing energy consumption, to operate and manage costs of street lighting as well as to improve citizens' safety and visual comfort. In this regard, simulation is one of the most helpful and promising techniques to implement lighting optimization. Simulation allows the optimization of the use of lighting by revealing the maximum savings, i.e., minimizing electricity consumption per lux while complying with mandatory regulations and comfort indices. International Commission on Illumination (CIE) establishes the lighting requirements for outdoor lighting installations on roads with motor and pedestrian traffic according to lighting classes [20]. However, lighting simulation is still challenging because of the complexity of reflecting the real conditions of an environment and the users' needs within the environment. Baloch et al. [12] conducted a detailed investigation of the most popular lighting simulation tools, their applications and associated parameters, concluding that MATLAB is the most popular simulation tool for general purposes. Shaikh et al. [21] developed a multiagent control system with stochastic intelligent optimization in MATLAB, achieving an energy efficiency of 31.6%. Other authors have used tools such as EnergyPlus [22], DOE [23], Daysim [24], BuildOpt [25] or Radiance [26]. Bustamante et al. [27] used EnergyPlus and Radiance to evaluate two complex fenestration systems (CFS) in four different cities using mkSchedule as a tool to determine the maximum allowable irradiance that minimizes the energy consumption while meeting the visual comfort criteria. Vera et al. [28] combined EnergyPlus, Radiance and GenOpt [29] with the hybrid particle swarm optimization/Hooke–Jeeves (PSO/HJ) algorithm to perform the lighting simulation concluding that the optimization process is efficient and robust.

This article presents a novel methodology to reliably reflect the real outdoor lighting conditions in order to perform lighting optimization. Lighting simulation is accomplished using Radiance, and optimization is implemented by developing a deterministic calibration method using the PSO/HJ algorithm. Next, the complete procedure is assessed and validated by means of two different case studies: (i) a single street lamp facility in a dark room recreating real conditions, (ii) and a real road lighting facility applied to a specific real scene in Málaga, Spain. Although this study is validated in outdoor lighting conditions, its findings are also relevant to indoor lighting. The methodology described in this paper can be useful for street lighting maintenance, assessment of roadway conditions or street lighting regulation because it accurately reflects real conditions.

2. Methodology

The methodology proposed in this work can be observed in Figure 1, and it has two stages: (i) Modeling and simulation of artificial lighting using Radiance, developed by the Lawrence Berkeley National Laboratory, as a physically based lighting simulation engine to recreate the environmental conditions of a road; (ii) calibration of the lighting model by adjusting the maintenance factor of each luminaire according to the illuminance measured experimentally on the road using GenOpt in combination with Radiance.

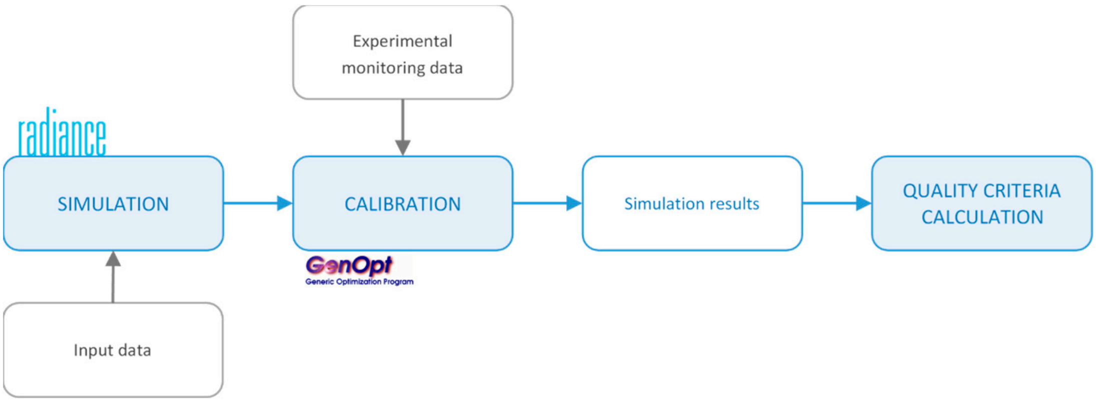


Figure 1. Simulation and calibration methodology diagram.

2.1. Modeling and Simulation of Artificial Lighting

First, a lighting scene is modeled using Radiance and following the procedure recommended by Ward et al. [26] for roadway lighting, including information about geometry and materials of the objects, the arrangement of artificial lights that make up the lighting system provided by lighting manufacturers and the sky radiance distribution. Radiance is a suite of tools that must be combined properly in order to carry out a lighting simulation. In this work tools like gensky, oconv or ies2rad are used to model the scene while rtrace or rcalc allow to perform the calculations related to the simulation.

The geometric model is elaborated in the simulation software, taking into account the characteristics of the objects. To simplify the model, the objects represented are the road, the lampposts and the luminaires in the analyzed area.

Following the classification applied by Radiance, the lampposts' material is modeled as metal to account for the specular component in the way light is reflected. In the case of road pavement, a more complex definition of material is used considering that there is a strong specular component in some source and viewing angles. The amount of light reflected on the surface of a road depends on the attributes of the pavement, the position of the observer and the point that the observer is visualizing, as well as the direction of the incident light at that point. For this work, the pavement description system established by the CIE in CIE 30-1976 [30] is adopted. A specular factor (S) and an average luminance coefficient (Q0) are used in the definition of the road material, whose values are standardized by the CIE (CIE 140-2000) [31] according to the type of pavement. To take into account all the parameters that influence the reflection of the light in the asphalt, the r-tables are used. The r-tables contain the reduced luminance coefficient in the angular intervals and in the directions given by the angles β (angle between plane of light incidence and plane of observation) and γ (angle of light incidence), considering α (angle of observation) at a constant value equal to 1°. The standard values for the reduced luminance coefficients are defined in the CIE 144: 2001 [32] standard for each of the road classes.

Light sources are modeled based on their geometry and light properties, which is provided by manufacturers. The light information is presented in photometric files in the format of the lighting standard of Illuminating Engineering Society (IES). This type of file has the information that defines the luminance behavior of the luminaire. From the IES photometric file, the luminous distribution of the luminaire is extracted by the Radiance program ies2rad, which is represented by intensity tables for different planes and angles of light incidence.

The description of the scene is completed using gensky to generate the radiance distribution of the sky. The nighttime sky is represented by a glowing dome without sun, thus trying to approximate the radiation values that are reached at ground level. The installation location is taken into account by specifying factors such as latitude and longitude.

The complete model is generated through the oconv tool that creates an octree from the scene description files. The process continues with the simulation of the scene. Radiance is based on the backward ray tracing tracking algorithm to simulate light propagation [33]. The rtrace program is used to evaluate irradiance at the indicated coordinates from a point of view and gives the result in a RGB numerical value. Illuminance is calculated from irradiance by executing the rcalc tool.

2.2. Calibration of the Lighting Scene

With the aim of minimizing the errors made in the representation of the scene because of the simplifications and approximations applied, the model is subjected to a calibration process. A deterministic calibration methodology (shown in Figure 2) has been developed by implementing the Hooke–Jeeves algorithm, based on generalized pattern search (GPS). It is a hybrid algorithm for global optimization. This algorithm is implemented through GenOpt software, a tool that minimizes cost functions by working together with other simulation programs such as Radiance [29].

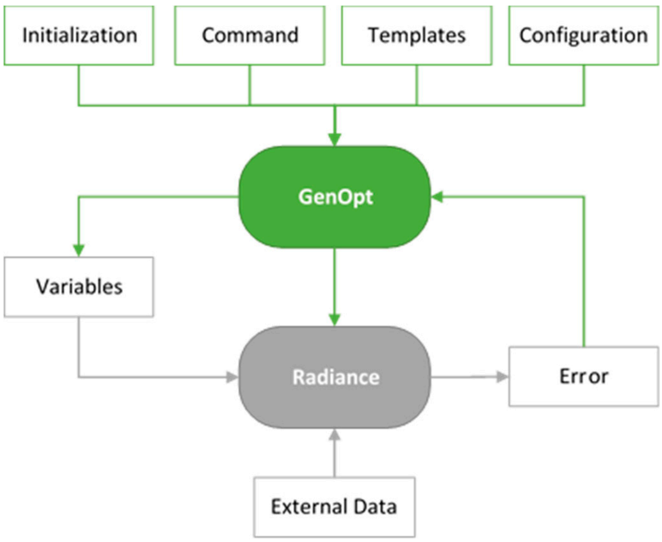


Figure 2. Calibration methodology applied to the simulation of outdoor lighting installations.

The Hooke–Jeeves search pattern method [34] creates a set of search directions iteratively combining exploratory moves with pattern moves or accelerations, both regulated by some heuristic rules. Therefore, an iterative process is applied. The process starts with the variables adopting a specified initial value and iteratively GenOpt applies the algorithm to vary the selected parameters, whether discrete or continuous, among the range of possible values considering the established limits. For each iteration, GenOpt executes the combination of Radiance programs with the allocated values and then calculates the cost of the objective function analyzing if it reaches optimal results. Consequently, a comparison can be established between the model predictions and the measurements obtained experimentally.

The coefficient of variation of the root mean squared error CV(RMSE) is the statistical index used to verify the results [35], which can be expressed as Equation (1), where $\hat{y}_i$ is the variable measure,

y_i represents the predicted value, $\overline{y}$ indicates the arithmetic mean of the measured samples and n is the number of measures.

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\frac{1}{n}\sum_{n=1}^{n}(\hat{y}_i - y_i)^2}}{\overline{y}} \quad (1)$$

In this work, the error is calculated considering the illuminance measured during the experimental data acquisition stage and the expected illuminance as a result of the simulation methods. The choice of factors that are varied depends on the conditions in which the experiment is performed but the calibration process mainly focuses on the modification of parameters that represent the individual maintenance factor of each luminaire.

The maintenance factor is calculated as indicated in CIE 154:2003 [36] depending on the lumen depreciation of the luminaire, the probability of lamps continuing in operation after a specific time and the accumulation of dirt on lamps and luminaires. The maintenance factor reaches a value of 0.67 for a typical low-maintenance installation, similar to the experimental systems studied in this work that are typically comprised of widely used high pressure sodium (HPS) lights and IP6 luminaires installed in a high-pollution environment. It should be noted that a value close to 1 for this variable represents a recently installed lamp, while a low value indicates that the lamp's properties have been depleted.

The calibrated model can be used to audit the state of the installation by comparing the different parameters calculated as indicated by CIE 140:2000 [31], using Radiance or any other simulation software, and the specifications for each type of road indicated in CIE 115:2010 [20]. The parameters of interest include the average luminance (L_{av}), overall uniformity of luminance (U_0), longitudinal uniformity of luminance (U_l), threshold increment (TI) and surround ratio (SR).

3. Experimental System

The method was tested to verify its effectiveness through the comparison of experimental measurements and results of several simulations performed in a simple installation in a controlled environment and in a more complex installation of a real road with actual traffic.

3.1. Single Street Lamp Facility

First, the experiments were conducted in a dark room with black walls and no natural light. The facility consists of a single street lamp, model VL-250 luminaire from the manufacturer Carandini (Barcelona, Spain), located on a column 3 m high and with an overhang of 1 m and one 150 W HPS light source.

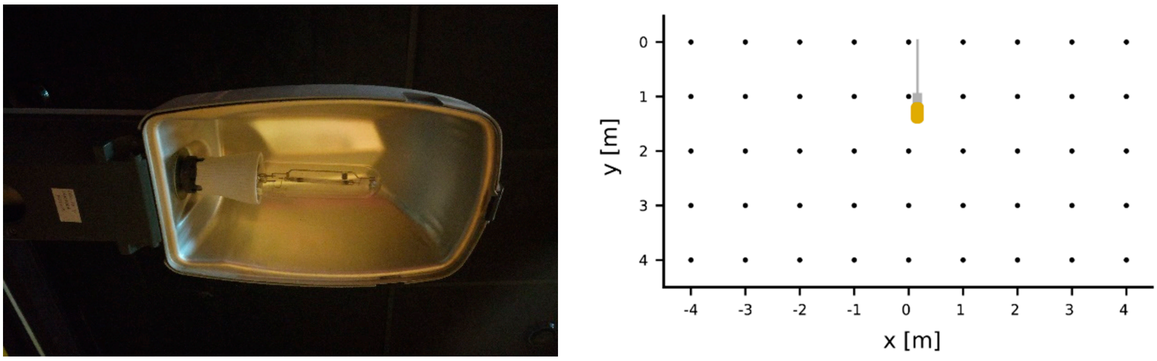
Four experiments were carried out (E1, E2, E3 and E4) considering two similar light bulbs, from the manufacturers Philips (Amsterdam, Netherlands) and GE Lighting (OH, USA), and two different lamp configurations. The complete luminaire was installed (model VL-250/M) in two of the experiments while for the others, the luminaire was set up without the polycarbonate bowl (model VL-250/A), such as two different luminaires with two different photometric distributions. Table 1 lists information about the conducted experiments.

Table 1. Experiments combining different types of luminaires and lamps.

Experiment ID	Luminaire Model	Lamp Model	Power [W]	Luminous Flux [lm]
E1	VL-250/M	PHILIPS MASTER SON-T PIA Plus 150 W	150	17700
E2	VL-250/A	PHILIPS MASTER SON-T PIA Plus 150 W	150	17700
E3	VL-250/M	GE Lucalox LU150/100/XO/T/40	150	17600
E4	VL-250/A	GE Lucalox LU150/100/XO/T/40	150	17600

Luminaires with a high number of hours of operation were used in order to easily determine the losses that occur owing to the aging of the lamp and other factors such as dirtying, deterioration of the reflector or the erosion of the luminaire materials.

The data acquisition system used was an illuminance meter. The measurements were taken in a grid of 9 × 5 points on the ground plane separated from each other 1 m apart as indicated in Figure 3. This information was used for the calibration process which was focused to modify the maintenance factor of the installed luminaire.



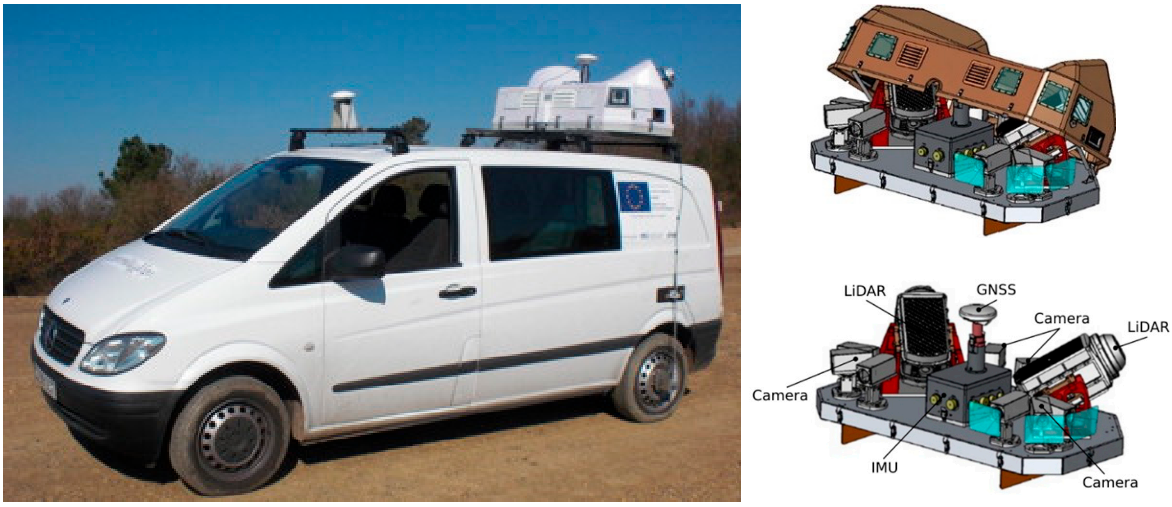
(**a**) (**b**)

Figure 3. Experimental system details: (**a**) luminaire; and (**b**) grid of 9 × 5 on the ground plane where the luminance was measured.

3.2. Road Street Lighting Facility

In the second set of experiments, the methodology was applied to a specific scene, located in the city of Málaga, Spain. The two-lane road considered in the experiment is approximately 330 m long and 7 m wide and includes 12 street lights. They are separated from each other at varying distances and are installed on one side of the road. Each luminaire is mounted on the top of a 13 m pole with an overhang of 1 m and involves one 250 W HPS light source. According to the CIE road surface classification CIE 30-1976 [30], the road pavement is considered as R3 whereas the light class can be considered M4 as per CIE 115:2010 [20].

Geometrical information about the road involved in the scene was acquired through the automatic processing of mobile laser scanning (MLS) point clouds. MLS represents the latest in Light Detection and Ranging (LiDAR) technology. The luminaire detection methodology developed by Puente et al. [37] for the detection of luminaires in tunnels was applied too, which provides precise coordinates to position the luminaires on the road. Data were collected using the Optech Lynx Mobile Mapper showed in Figure 4. The mobile system is composed of two LiDAR sensors, an illuminance meter, four digital cameras and a navigation system with global navigation and inertial measurement units (IMU) with a two-antenna heading measurement system, called global navigation satellite system (GNSS). A complete accuracy study and system review can be found in Puente et al. [38].

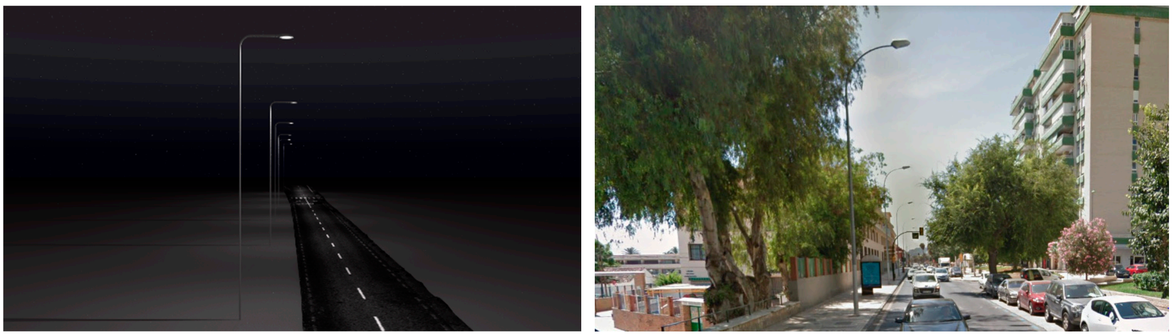


(**a**) (**b**)

Figure 4. Optech Lynx mobile mapper used for the data collection: (**a**) vehicle; and (**b**) depiction of the system and the equipment installed on the vehicle [39].

Figure 5 shows a rendering of the scene, in which the arrangement of luminaires and horizontal road signs are presented. Horizontal signs were obtained using automatic detection algorithms developed by Riveiro [39].

The information generated by LiDAR techniques can be used for the modeling of scenes in Radiance thanks to the versatility of the tool that can be adapted and work with complex geometries of objects such as point clouds. The combination of data collection techniques with open source simulation software allows to automate the process and reduce the time invested in the development of the task.



(**a**) (**b**)

Figure 5. Lighting scene used on the simulation and the calibration process: (**a**) 3D rendering and; (**b**) real scene.

The experimental measures of the illuminance were taken in a direction longitudinal to the road as the vehicle crosses the route. A sample of 127 points separated from each other by 2–3 m was collected. For mobile experiments, a discrepancy between the illuminance data and the coordinates collected is produced owing to the sensor response time. Considering that the vehicle that incorporates the measuring equipment moves at a constant speed, in addition to the depreciation of the luminaires, a new calibration parameter is taken into account, representing the delay that the sensor introduces in the measurements.

4. Results and Discussion

Results concerning the two proposed systems are presented and analyzed in this section. First, the methodology is applied in a controlled environment with a single luminaire; later, the procedure is repeated in a real scene with 12 luminaires.

4.1. Single Street Lamp Results

For each longitudinal section of the calculation grid described in Figure 3 and for each experimental system considered, the illuminance data collected for point (E_{exp}), the illuminance results of the initial simulation (E_{sim}) and the results of the simulation with the calibrated model (E_{simCal}) are shown in Figure 6. The graphs show the accuracy of the methodology. The results obtained from the calibrated simulation approximate the illuminance measured experimentally for the four study cases analyzed, especially in the areas closest to the luminaire, in which the value of the illuminance is higher, and therefore, so is the error produced. Figure 6 also includes the results of the simulation carried out under the assumption that the lamp has been installed recently and, therefore, has not suffered any depreciation of its properties.

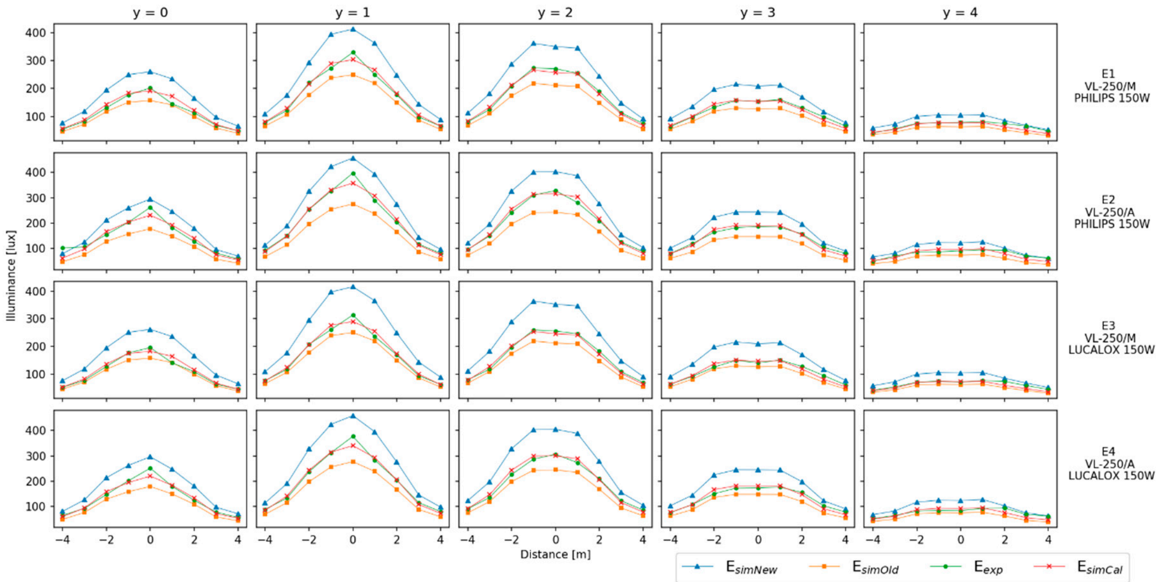


Figure 6. Illuminance in the longitudinal sections of the calculation grid considered (Figure 2) (E_{exp}: experimental illuminance; E_{simCal} and E_{simOld}: simulated illuminance after and before calibration; and E_{simNew}: simulated illuminance supposing that the lamps are newly installed).

Through the calibration process, it has been estimated that the installed luminaires for the experimental tests have suffered a reduction of 20–30% in their maintenance factor, as given in Table 2. Comparison with experiments in which the same model of light bulb has been included evinces that not only has the light source suffered losses, the complete luminaire has also aged. Tests in which the polycarbonate bowl has been installed (E1 and E3) provided a lower value for the calibrated variables, indicating that dirt and deterioration of the luminaires' materials have a negative impact on the lighting levels offered.

Table 2. Value of the Maintenance Factor and the CV(RMSE) for the different experiment cases, before and after calibration.

Experiment ID	Design Value	Calibrated Value	CV(RMSE) Initial Simulation	CV(RMSE) Calibrated Simulation	Reduction
E1	0.67	0.816	21.75%	7.23%	66.76%
E2	0.67	0.871	27.50%	8.27%	69.93%
E3	0.67	0.775	17.11%	7.14%	58.27%
E4	0.67	0.824	22.61%	7.59%	66.43%

In Table 2, the CV(RMSE) calculated for each experimental system is presented, matching the uncalibrated simulation with the calibrated one. After the calibration process, the metrics decrease by 58–70% depending on the experiment, achieving values lower than 8.27% for the CV(RMSE).

4.2. Road Street Lighting Results

Figure 7 shows the illuminance in several points of the analyzed sample, comparing the experimental data collected and the simulation results before and after the application of the calibration methodology. The calibration approximates the results of the initial simulation to the measurements collected. The similarity of the shape between calibrated simulation and experimental curves is high. The top values of illuminance correspond to areas very close to luminaires while the lower ones are more distant areas. This allows identification in the graph of the positions in which the light spots and the distances between them are located. The comparison of the curves resulting from the calibrated and uncalibrated simulation provides evidence that the deterioration cannot be considered uniform for all luminaires, being independent for each of them. The inclusion of the sensor delay in the calibration process prevents gaps between the results of the simulation and the real data, improving the method without increasing the computational cost.

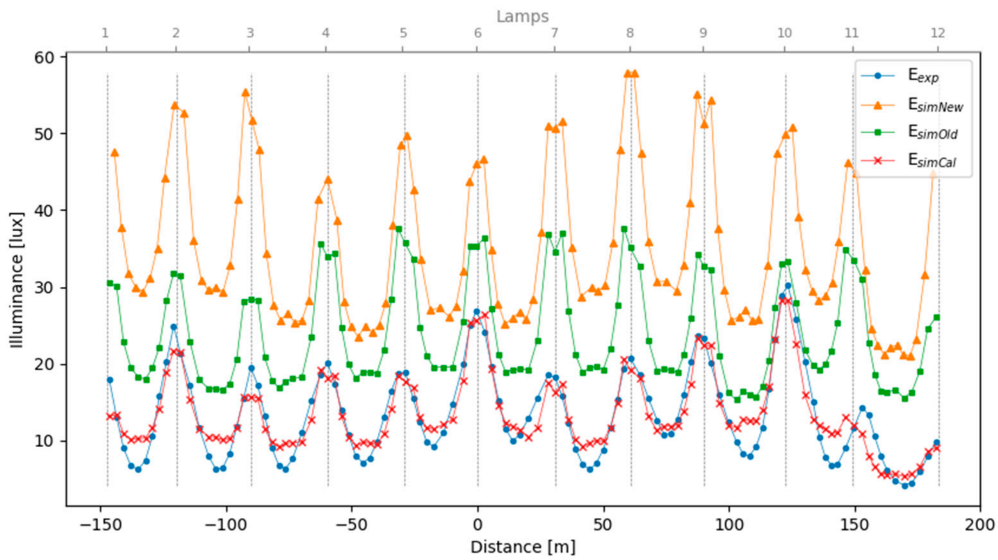


Figure 7. Illuminance at the points of the sample analyzed. (E_{exp}: experimental illuminance; E_{simCal} and E_{simOld}: simulated illuminance after and before calibration; and E_{simNew}: simulated illuminance supposing that the lamps are newly installed)

Table 3 includes the variables considered in the calibration and the values obtained at the end of the process. The results evince that the lamps in the case study show a behavior far removed from the behavior that is theoretically expected, which might be because of the high number of operational hours, the dirt or other technical defects. The analysis of the maintenance factor can facilitate decision-making in order to improve the efficiency of the installation, by identifying luminaires with inferior performance.

Table 3. Variables of the model for calibration process.

ID	Variable	Design Value	Calibrated Value
X1	Maintenance Factor street Lamp 1	1	0.269
X2	Maintenance Factor street Lamp 2	1	0.485
X3	Maintenance Factor street Lamp 3	1	0.360
X4	Maintenance Factor street Lamp 4	1	0.362
X5	Maintenance Factor street Lamp 5	1	0.317
X6	Maintenance Factor street Lamp 6	1	0.509
X7	Maintenance Factor street Lamp 7	1	0.230
X8	Maintenance Factor street Lamp 8	1	0.364
X9	Maintenance Factor street Lamp 9	1	0.458
X10	Maintenance Factor street Lamp 10	1	0.615
X11	Maintenance Factor street Lamp 11	1	0.205
X12	Maintenance Factor street Lamp 12	1	0.235
X13	Delay illuminance sensor [m]	0	−51.00

The CV(RMSE) that quantify the error in the simulations performed are calculated. The values listed in Table 4 show that, through calibration, a reduction of error by 80% is achieved by considering the variables that represent the aging of each street lamp and the delay of the light sensor. The CV(RMSE) reaches a value of 16.57% for the calibrated simulation.

Table 4. Values of the CV(RMSE) for the initial simulation and after the calibration of the simulation.

Statistical Error	Initial Simulation	Calibrated Simulation	Reduction
CV(RMSE)	84.19%	16.57%	80.31%

Taking into account the lighting class and ensuring that the requirements of the CIE 115:2010 standard are met, it is verified that the installation status is not adequate to provide the required services, as detailed in the Table 5. The parameters that quantify the disability glare (threshold increment) and the lighting of the surrounding areas achieve acceptable values as per the regulations, as well as according to some of the road surface luminance criteria of the carriageway (overall and longitudinal uniformity). However, the average luminance requirement is not fulfilled.

Table 5. Average luminance (L_{av}), overall uniformity of luminance (U_0), longitudinal uniformity of luminance (U_l), threshold increment (TI) and surround ratio (SR) of the road between Lamp 6 and Lamp 7 of the system.

Simulation results			CIE 115:2010
L_{av}	0.82	$\geq$	1
U_0	0.56	$\geq$	0.4
U_l	0.76	$\geq$	0.6
TI	6	$\leq$	15
SR	0.73	$\geq$	0.5

Figure 8 displays false color renderings of the road surface as seen from the observer position, showing the light distribution in terms of luminance and illuminance. The results agree with the aging factors established for the simulation after the calibration process (Table 3). The higher illumination values are positioned around Lamp 6, which has suffered less deterioration.

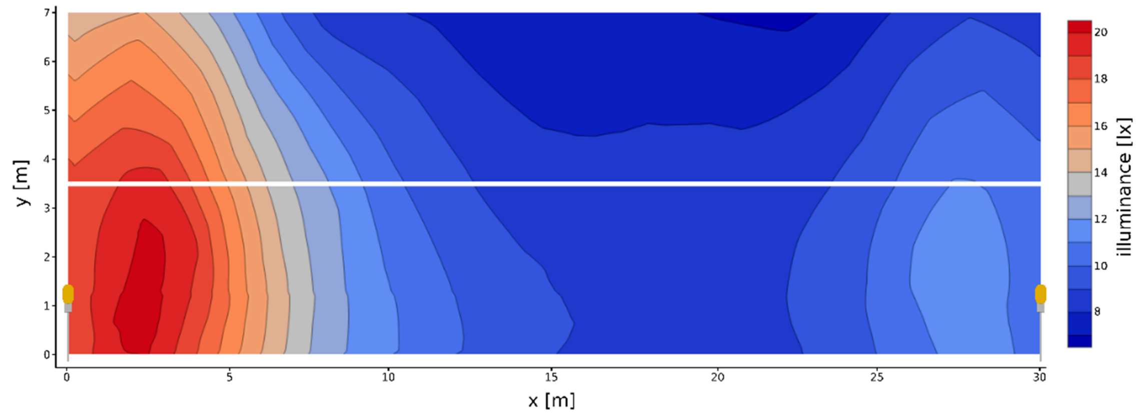


Figure 8. False color view for the illuminance [lux] of the two-lane road between Lamp 6 and Lamp 7 of the system.

5. Conclusions

In this paper, a method for modeling and calibrating outdoor lighting installations is presented and applied to two different cases: a first case study, composed of a single luminaire (studied under different configurations), was designed to test the methodology in a controlled environment, and a second case study, simulating a real scene composed of 12 luminaires distributed along a road and located in the south of Spain, allowed the validation of the process in more complex conditions and with the added complication of using measurements collected in motion for the calibration.

The methodology provides simulated illuminance measurements at points of a mesh positioned at different distances from the luminaire, taking into account the deterioration suffered over time by the group formed by lamp and luminaire. The first experimental system proves that the method is feasible for various configurations and ages of luminaires and light sources, reducing the CV(RMSE) below 9%.

The application of the process to a more complex scene shows that by adding the delay of the light sensor in the measurement as a calibration parameter, errors produced during the data collection of experimental illuminance can be corrected and the CV(RMSE) decreased by 80%. The identification of the real maintenance factor of each luminaire facilitates decision-making to improve the efficiency of the installation by recognizing the street lamps with poor performance. In addition to allowing the reproduction of the actual lighting conditions of a scene, the method can potentially be used in the identification of the lighting technology and model of the luminaire among a range of possibilities when these characteristics are unknown or uncertain.

The results of this work showed that, used together, Radiance and GenOpt form a useful tool to calibrate and simulate lighting models and to evaluate the features offered by outdoor lighting installations.

Author Contributions: Conceptualization, A.O.-M.; Data curation, J.L.-G.; Investigation, A.O.-M. and J.L.-G.; Methodology, A.O.-M.; Resources, J.L.-G. and L.F.-G.; Software, A.O.-M.; Supervision, L.F.-G.; Validation, J.L.-G. and L.F.-G.; Visualization, L.F.-G.; Writing—original draft, A.O.-M., J.L.-G. and L.F.-G.

Acknowledgments: Authors want to give thanks to the Xunta de Galicia (Grant ED481A). This investigation article was partially supported by CANDELA project, through the Xunta de Galicia CONECTA PEME 2016 (IN852A/81).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this article:

IEA	International Energy Agency
EU	European Union
GHG	Greenhouse Gases
LED	Light Emitting Diode
CFS	Complex Fenestration Systems
PSO/HJ	Particle Swarm Optimization / Hooke-Jeeves
IES	Illuminating Engineering Society
CIE	International Commission on Illumination
MLS	Mobile Laser Scanning
LiDAR	Laser Imaging Detection and Ranging
IMU	Inertial Measurement Units
GNSS	Global Navigation Satellite System
CV(RMSE)	coefficient of variation of the root mean squared error

References

1. Waide, P.; Tanishima, S.; International Energy Agency. *Light's Labour's Lost. Policies for Energy-Efficient Lighting*; OECD Publications: Paris, France, 2006.
2. Nardelli, A.; Deuschle, E.; de Azevedo, L.D.; Pessoa, J.L.; Ghisi, E. Assessment of Light Emitting Diodes technology for general lighting: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 368–379. [CrossRef]
3. IEA. Available online: https://www.iea.org/about/ (accessed on 18 August 2018).
4. EU 2030 Climate & Energy Framework. Available online: https://ec.europa.eu/clima/policies/strategies/2030_en (accessed on 18 August 2018).
5. Thielemans, S.; Di Zenobio, D.; Touhafi, A.; Lataire, P.; Steenhaut, K. DC Grids for Smart LED-Based Lighting: The EDISON Solution. *Energies* **2017**, *10*, 1454. [CrossRef]
6. Lighting Europe. Available online: https://www.lightingeurope.org/ (accessed on 18 August 2018).
7. Montoya, F.G.; Peña-García, A.; Juaidi, A.; Manzano-Agugliaro, F. Indoor lighting techniques: An overview of evolution and new trends for energy saving. *Energy Build.* **2017**, *140*, 50–60. [CrossRef]
8. Chang, M.H.; Das, D.; Varde, P.V.; Pecht, M. Light emitting diodes reliability review. *Microelectron. Reliab.* **2012**, *52*, 762–782. [CrossRef]
9. Liu, H.; Zhou, Q.; Yang, J.; Jiang, T.; Liu, Z.; Li, J. Intelligent Luminance Control of Lighting Systems Based on Imaging Sensor Feedback. *Sensors* **2017**, *17*, 321. [CrossRef] [PubMed]
10. Troncoso-Pastoriza, F.; Eguía-Oller, P.; Díaz-Redondo, R.P.; Granada-Álvarez, E. Generation of BIM data based on the automatic detection, identification and localization of lamps in buildings. *Sustain. Cities Soc.* **2018**, *36*, 59–70. [CrossRef]
11. Soori, P.K.; Vishwas, M. Lighting control strategy for energy efficient office lighting system design. *Energy Build.* **2013**, *66*, 329–337. [CrossRef]
12. Baloch, A.A.; Shaikh, P.H.; Shaikh, F.; Leghari, Z.H.; Mirjat, N.H.; Uqaili, M.A. Simulation tools application for artificial lighting in buildings. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3007–3026. [CrossRef]
13. Haq, M.A.u.; Hassan, M.Y.; Abdullah, H.; Rahman, H.A.; Abdullah, M.P.; Hussin, F.; Said, D.M. A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renew. Sustain. Energy Rev.* **2014**, *33*, 268–279. [CrossRef]
14. Corte-Valiente, A.; Castillo-Sequera, J.; Castillo-Martinez, A.; Gómez-Pulido, J.; Gutierrez-Martinez, J. An Artificial Neural Network for Analyzing Overall Uniformity in Outdoor Lighting Systems. *Energies* **2017**, *10*, 175. [CrossRef]
15. Castillo-Martinez, A.; Ramon Almagro, J.; Gutierrez-Escolar, A.; del Corte, A.; Castillo-Sequera, J.; Gómez-Pulido, J.; Gutiérrez-Martínez, J. Particle Swarm Optimization for Outdoor Lighting Design. *Energies* **2017**, *10*, 141. [CrossRef]
16. Yoomak, S.; Jettanasen, C.; Ngaopitakkul, A.; Bunjongjit, S.; Leelajindakrairerk, M. Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system. *Energy Build.* **2018**, *159*, 542–557. [CrossRef]

17. Gago-Calderón, A.; Hermoso-Orzáez, M.; De Andres-Diaz, J.; Redrado-Salvatierra, G. Evaluation of Uniformity and Glare Improvement with Low Energy Efficiency Losses in Street Lighting LED Luminaires Using Laser-Sintered Polyamide-Based Diffuse Covers. *Energies* **2018**, *11*, 816. [CrossRef]
18. Fotios, S.; Qasem, H.; Cheal, C.; Uttley, J. A pilot study of road lighting, cycle lighting and obstacle detection. *Light. Res. Technol.* **2017**, *49*, 586–602. [CrossRef]
19. Moretti, L.; Cantisani, G.; Di Mascio, P. Management of road tunnels: Construction, maintenance and lighting costs. *Tunn. Undergr. Space Technol.* **2016**, *51*, 84–89. [CrossRef]
20. *CIE 115:2010 Lighting of Roads for Motor and Pedestrian Traffic*; International Commission on Illumination: Vienna, Austria, 2010.
21. Shaikh, P.H.; Nor, N.B.M.; Nallagownden, P.; Elamvazuthi, I.; Ibrahim, T. Intelligent multi-objective control and management for smart energy efficient buildings. *Int. J. Electr. Power Energy Syst.* **2016**, *74*, 403–409. [CrossRef]
22. Energyplus. *EnergyPlus Engineering Reference*; US Department of Energy: Washington, DC, USA, 2010.
23. York, D.A.; Cappiello, C.C. *DOE-2 Engineers Manual*; Lawrence Berkeley Lab: Berkeley, CA, USA; Los Alamos National Lab: Los Alamos, NM, USA, 1981.
24. Reinhart, C.F.; Walkenhorst, O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* **2001**, *33*, 683–697. [CrossRef]
25. Wetter, M. BuildOpt—A new building energy simulation program that is built on smooth models. *Build. Environ.* **2005**, *40*, 1085–1092. [CrossRef]
26. Larson, G.W.; Shakespeare, R. *Rendering with Radiance: The Art and Science of Lighting Visualization*; Booksurge Llc: San Francisco, CA, USA, 2004.
27. Bustamante, W.; Uribe, D.; Vera, S.; Molina, G. An integrated thermal and lighting simulation tool to support the design process of complex fenestration systems for office buildings. *Appl. Energy* **2017**, *198*, 36–48. [CrossRef]
28. Vera, S.; Uribe, D.; Bustamante, W.; Molina, G. Optimization of a fixed exterior complex fenestration system considering visual comfort and energy performance criteria. *Build. Environ.* **2017**, *113*, 163–174. [CrossRef]
29. Wetter, M. GenOpt®—A Generic Optimization Program. In Proceedings of the Seventh International IBPSA Conference, Rio de Janeiro, Brazil, 13–15 August 2001; pp. 601–608.
30. *CIE 30-1976 Calculation and Measurement of Luminance and Illuminance in Road Lighting*; International Commission on Illumination: Vienna, Austria, 1976.
31. *CIE 140-2000 Road Lighting Calculations*; International Commission on Illumination: Vienna, Austria, 2000.
32. *CIE 144:2001 Road Surface and Road Marking Reflection Characteristics*; International Commission on Illumination: Vienna, Austria, 2001.
33. Ward, G.J. The RADIANCE Lighting Simulation and Rendering System. In Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH), Orlando, FL, USA, 24–29 July 1994; pp. 459–472.
34. Wetter, M. *GenOpt Generic Optimization Program, User Manual*; Version 3.1.1; Simulation Research Group, Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2016.
35. Ruiz, R.G.; Bandera, F.C. Validation of Calibrated Energy Models: Common Errors. *Energies* **2017**, *10*, 1587. [CrossRef]
36. *CIE 154:2003 The Maintenance of Outdoor Lighting Systems*; International Commission on Illumination: Vienna, Austria, 2003.
37. Puente, I.; González-Jorge, H.; Martínez-Sánchez, J.; Arias, P. Automatic detection of road tunnel luminaires using a mobile LiDAR system. *Measurement* **2014**, *47*, 569–575. [CrossRef]
38. Puente, I.; González-Jorge, H.; Riveiro, B.; Arias, P. Accuracy verification of the Lynx Mobile Mapper system. *Opt. Laser Technol.* **2013**, *45*, 578–586. [CrossRef]
39. Riveiro, B.; González-Jorge, H.; Martínez-Sánchez, J.; Díaz-Vilariño, L.; Arias, P. Automatic detection of zebra crossings from mobile LiDAR data. *Opt. Laser Technol.* **2015**, *70*, 63–70. [CrossRef]