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Energy efficiency of lighting installations: Software application and experimental validation

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ABSTRACT

The rational use of energy and energy-efficient environmental public street lighting is an important topic. In the design of new public lighting installations, national regulations containing energy-efficient guidelines are already used. Nevertheless, either in new installations or in reconstructions of existing lighting, designers do not generally consider all the available means to save energy. In installations of street lighting, energy consumption can be reduced by reducing the losses in the conductors, associated with the efficiency of the equipment, allowing better use of the available energy. The losses in the conductors must be analysed in conjunction with all the loads that contribute to the current in the sections of the installed street lighting. When opting for more efficient lamps and luminaires or lighting control systems, the current decreases in the sections covered with the most significant power loss due to proportionality with the square of the current. This decrease, often forgotten, is considered in this work in the investment analysis of efficiency and sustainable street lighting via simulation and experimental results. This analysis, combined with the features and operating parameters of the electrical installation, accounts for all the gains that can make a difference in the choice of efficient street lighting.

1. Introduction

This paper presents a new software application and experimental validation to compare and choose the best investment in the solutions of street lighting installations. This analysis takes into account the decrease in the consumption of the lamps and the losses in the electrical conductors, which are usually forgotten. The power losses in the conductors, being proportional to the resistance and the square of the current, must be considered together with all the loads that contribute to the current in the sections of the installation, to account for all the gains that can make a difference in the choice of installation of efficient street lighting.

The choice of efficient street lighting is related to the following factors: price, power consumption, reduction of losses in the conductors, useful life and interest rate. This study will be based on a new way of thinking: from minimal investment cost to minimal life cycle cost.

At a time when the prediction for energy consumption is a global increase of 38.6% by the year 2030, the imperative to pursue energy-efficient improvements is clearly on the political agenda at all levels of government. Referring to the actions proposed, in 2008, a response document was produced by the IEA (International Energy Agency) to the document request for policy advice on energy efficiency across the Action Plan of the G8 in Gleneagles (Jollands et al., 2010). The recommendations for energy efficiency cover 25 fields of action in 7 priority areas: buildings, appliances, lighting, transport, industry, energy utilities and cross-sectoral issues. Decision makers and policy makers will be able to base their actions on real-world, real-time data. Households and companies will be able to react to market fluctuations by increasing or decreasing their consumption or production, thus directly contributing to increased energy efficiency.

Energy efficiency and consumption reduction in electrical installations and equipment have been the subject of investigation and research, from energy production to the final consumer. Public (predominantly street) lighting contributes 2.3% to the global electricity consumption; thus, energy-efficient programmes in this field are very welcome, since the possibilities for energy savings in

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Nomenclature

E_P	Illuminance in the point P
E_{av}	The average illuminance
L_v	Veiling luminance equivalent
TI	Glare upsetting/Threshold increment
$\underline{L}$	Luminance
$\bar{L}$	Average luminance
η	Luminous efficiency
ε	Energy efficiency of the installation
S	Area
E	Medium level of service calculated illuminance
KC	Knot Connection
B	Branch
R	Net profit
D	Operation cost
V	Residual value
Inv	New investment
d	Monthly operating days
m	Months of annual operation
€	Cost of electricity
ΔP	Difference in cable losses
P	Power
$\Delta P[k, i]$	Difference in cable losses of the conductor of the output i of the distribution boxes K
$R[k, i]$	Resistance of the conductor of the output i of the Knot Connection
$I[k, i]$	Current of the conductor of the output i of the Knot Connection
N_i	Initial investment
O_i	Mean annual savings
SPP	Simple Payback Time
VAL	Net Present Value
IRR	Internal Rate of Return
I	Current
D	Operation cost
a	Annual interest rate
€	Electricity cost

street lighting are numerous and since some of them even enable reductions in electricity consumption of more than 50%.

The cable losses analysed regularly throughout the transport and distribution of energy are often overlooked as a component of the cycle of lighting systems and an available means to save energy and improve the overall performance of the installation of street lighting.

In power production, transport, distribution and final consumption, various aspects have been particularly highlighted: environmentally and economically efficient production and dispatch; distributed generation and significant impacts on the operational characteristics of transport and distribution networks (Alvarez-Herault et al., 2012); dimensioning of the section of the conductor selection circuit to reduce the power consumption and optimize the operating distribution systems; reduction of distribution losses by reducing the reactive power optimization with capacitors placed on the distribution lines and layout optimization for radial distribution (Pires et al., 2012); use of superconducting power transmission (Vysotsky et al., 2011); and the circuit design of industrial and residential electrical installations (Parise and Parise, 2011).

Also noteworthy is the study and development of efficient equipment in power consumption (Lobão et al., 2014), in particular industrial induction motors (Hamer et al., 1997), to be responsible for much of the energy consumption.

In the case of outdoor lighting, two situations can be identified: on the one hand decorative lighting, for which the aesthetic component is the main objective rather than obeying the requirements of lighting and energy, and on the other functional lighting for outdoors (streets, roads, squares, etc.).

Functional lighting accounts for a significant weight of energy consumption and contributes to the security of persons and property. Various aspects have been the subject of study and research.

From the aspect of security, there are regulations and national and international standards, which contain the values and rules to be complied with: the Document of the Reference for Energy-Efficient Public Illumination in Portugal, norm EN13201 and CIE 115:2010, among others (CEN Publication EN 13201, 2003; CIE Publication No 115, 2010).

With respect to energy efficiency and reducing the consumption of street lighting installations, we can separate the study into three aspects: one that includes the technological development of lamps and luminaires, as mentioned in Kostic et al. (2009), Hermoso Orzáez and de Andrés Díaz (2013), Sadhan Mahapatra and Chanakya (2009), Mahlia et al. (2011), Mockey Coureaux and Manzano (2013) and Sperber et al. (2012); another that includes the study and development of systems for the control of lamps and luminaires that under the project conditions allow the reduction of power consumption, for example the use of equipment that allows the variation in the luminous flux as a function of time and traffic conditions on the roads (Xiao et al., 2010; Burgos-Payan et al., 2012; Yan et al., 2009; Parise et al., 2013; Siddiqui et al., 2012); finally, we may consider integrating the two previous aspects into the installation of the whole system, for the purpose of classification of a public lighting installation from the point of view of energy and lighting (Radulovic et al., 2011; ADENE, 2011), into which we can integrate the present study.

In a street lighting installation, the reduction of energy consumption in order to improve energy efficiency has to contribute to the efficiency of the real lamps and losses in the cables of the installation, normally themes that are studied separately. It is intended to connect these two aspects of research, including, in the economic analysis, the influence of efficient lamps and the losses they cause in the installation. The selection of the connection between optimal cables and the influence of efficient lamps will also be demonstrated experimentally, in addition to the simulation results, providing an economic analysis. This paper is structured as follows. Section 2 presents a description of the formulation. Section 3 explains the economic evaluation. Section 4 illustrates the software application. Section 5 presents the results obtained in simulation and the experimental results. Finally, concluding remarks are given in Section 6.

2. Formulation

Good quality lighting design contributes good efficiency from the point of view of energy, security and illumination. The lighting class is not always identical for all the hours of the night. Therefore, it is up to the planners and designers, together with the entities responsible for public lighting (municipalities and dealership networks), to determine the selected classes throughout the night.

Illuminance is the ratio between the luminous flux emitted in all directions by a light source $\partial\varphi$ incident on an element surface and the area ∂A of this element. The unit is the lux (lx).

The illuminance at point P, E_P, of the road surface can be calculated using as a reference the representation of Fig. 1 and the light intensity I (cd) in a graph typically provided by the manufacturer of the luminaire used.

$$E_P = \left(\frac{I_{\vec{\gamma}}}{d^2}\right)\cos\gamma \qquad (1)$$

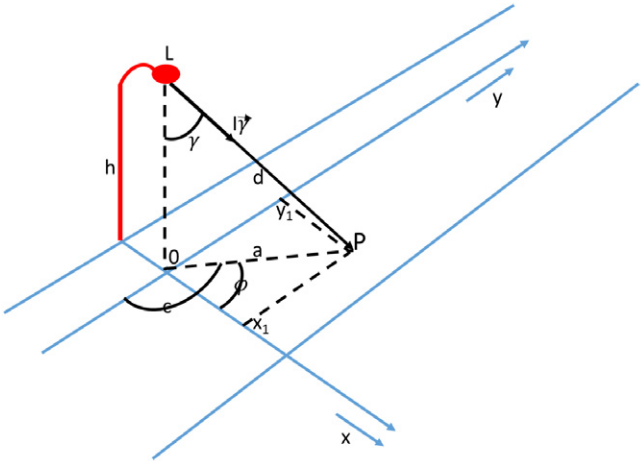

Fig. 1. Illuminance at a point P (E_P) of the road surface.

in which $\vec{\gamma}$ is the direction of the luminaire to the point P, and γ is the angle between h and the line that connects the luminaria and point P, as shown in Fig. 1.

$$d^2 = h^2 + a^2 = h^2 + x_1^2 + y_1^2 \tag{2}$$

$$\cos\gamma = \frac{h}{d} = \frac{h}{\sqrt{h^2 + x_1^2 + y_1^2}} \tag{3}$$

$$E_p = \frac{I_{\vec{\gamma}} \times h}{\left(h^2 + x_1^2 + y_1^2\right)^{\frac{3}{2}}} = \frac{I_{\vec{\gamma}}}{h^2} (\cos\gamma)^3. \tag{4}$$

The illuminance at point P due to n luminaires is given by:

$$E_P = \sum_{i=1}^{n} \frac{I_{\vec{\gamma}i}}{h^2} (\cos\gamma_i)^3. \tag{5}$$

The average illuminance will be calculated by:

$$E_{av} = \frac{\sum\limits_{j=1}^{n} (E_P)_j}{n}. \tag{6}$$

The values of the E_P of the j points due include longitudinal spacing between two consecutive luminaires and street width.

The luminance L is a measure of the density of the intensity of light reflected in a given direction, which describes the luminous flux that passes through or is emitted from a surface, according to a solid angle $\partial\Omega$.

The International System unit is the candela per square metre (cd/m^2). It can be understood as the quotient of light intensity I (cd) and the area A that reflects according to a given direction (θ-angle in degrees between the line of the arc and the line of sight from the viewer to the luminaire centre), that is:

$$L = \frac{I}{A \times \cos\theta} \; \left(\mathrm{cd/m^2}\right). \tag{7}$$

The average luminance is the arithmetic average of all the points. The upsetting glare, also known as the threshold increment *TI*, is a measure to quantify the loss of visibility caused by the glare of public lighting luminaires.

If it is intended for the object to be visible in these conditions, the level of contrast must be increased. This increment corresponds to the *TI* (ADENE, 2011; Ylinen et al., 2011):

$$TI = \frac{65}{(\bar{L})^{0,8}} L_v\% \tag{8}$$

and

$$L_v = 10 \sum_{k=1}^{n} \frac{E_k}{\theta_k^2} = \frac{E_1}{\theta_1^2} + \frac{E_2}{\theta_2^2} + \cdots + \frac{E_k}{\theta_k^2} + \cdots + \frac{E_n}{\theta_n^2} \tag{9}$$

$\bar{L}$-average luminance of the street (cd/m^2); L_v—luminance blinding (veiling luminance) equivalent (cd/m^2); E_K—illuminance (at lux based on the initial flux of the lamp in lumens) produced by luminaire k, on a plane normal to the line of sight and up to the observer's eye; θ—angle in degrees between the line of the arc and the line of sight from the viewer to the centre of the luminaire k.

In energy terms, we can refer to the luminous efficiency η of a luminaire and respective light source as the ratio of the total luminous flux emitted by the source φ and the power it has absorbed P. The unit of the International System is lm/W.

$$\eta = \frac{\varphi}{P} \; (\mathrm{lm/W}). \tag{10}$$

This ratio is also often referred to as the Energy Efficiency Index. If we consider not a luminaire and its components individually, but the total installation of a system of street lighting, we can define and classify the energy efficiency of an installation as the following equation:

$$\varepsilon = S\,\left(\mathrm{m^2}\right) \times E\;(\mathrm{lux})\,/P\;(\mathrm{W}) \tag{11}$$

ε—energy efficiency of the installation; S—area resulting from the product of the value of the distance between the points of light and the full width of the street; E—medium level of service calculated illuminance; P—total power of the luminaires, including the auxiliary equipment, intervening in the calculated area.

In order to improve the energy efficiency of a lighting system, various studies and developments have been undertaken, in terms of both technological and control systems. We observed, however, that the cable losses of installations are not considered.

In this work, we analyse the losses caused by the use of more efficient luminaires and control lighting throughout the night, in the installation cables depending on the use and the current path caused, to choose the lamps and/or the more efficient system, improving the energy rating of the installation.

2.1. *Identification of the parameters*

Physical parameters:

- Knot connection (KC).

The knot connections are numbered from 1 (the initial knot connection) to the total number of knot connections for the installation.

- Connections between knot connections.

The connections of these knot connections are saved in a matrix that identifies the connection courses. The number contained in the matrix $[k, i]$ indicates the number of the respective branch (B).

k: Knot connection that provides energy
i: Knot connection that receives energy
$[k, i]$: Branch in knot connection k.

For example:
Matrix connection $[1, 2] := 2$;
Knot connection (k) 1 provides power to knot connection (i) 2, the second branch.

- Length of branch conductors in the knot connection;
- Section of branch conductors in the knot connection.

From the length and section is determined the resistance of the conductors for all the branches.

The values are saved in a resistances matrix.
k: Knot connection; i: Branches; $[k, i]$: Value of resistances
For example:
Resistances matrix $[1, 2] := 1, 2$.
The branch resistances (i) 2 knot connection (k) 1 is 1, 2 Ω.
Load parameters:

- Power of the loads connected to the electrical installation;
- Efficiency of the loads;
- Power factor of the loads;
- Daily load diagram.

The load diagram is analysed within 24 h of the day, in intervals j.

• Daily load diagram of the lamps and system control for economic analysis.

Operating parameters:

- Operating time of the electrical installation;
- Monthly operating days (d);
- Months of annual operation (m);
- Cost of electricity (€).

The price of electricity is variable. The software allows the user to choose the tariff.

2.2. Installation characteristics

Fig. 2 shows a typical installation with the respective parameters. The streets of a residential neighbourhood are represented. The possibility of replacing the lamp that illuminates the facade LM street A by a more efficient La1 or La2 is studied, including the economic analysis losses in the branches B[k, i] (the branches are made of electrical cables) affected by the replacement, marked in bold in Fig. 2.

2.3. Calculations

After the input of the parameters and load diagrams, the following calculations are made:

- Determination of the load diagram associated with the branch knot connection, adding the corresponding load diagrams. Example: the branch “1” in “KC1” is the sum of the branch diagrams in “KC2” and the branch “2” in “KC2” is the sum of the branch diagrams in “KC3”.
- The currents in all the conductors of the electrical installation due to:
  - The initial load diagram ($I1[k, i]$), in branch B[2, 1] in Fig. 2.
  - The load diagram of the lamp La1 or La2 is more efficient ($I2[k, i]$), in branch B[2, 1] in Fig. 2.
- The difference in cable losses (ΔP) in the conductors affected by the changed lamp, where j are load diagram intervals, t_j arethe time intervals and $€_j$ is the price in the range variable throughout the day, are given by:

$$\Delta P\,[k,i] = \int_0^{24} R[k,i]\,(I1\,[k,i])^2\,d_t - \int_0^{24} R[k,i]\,(I2\,[k,i])^2\,d_t. \tag{12}$$

- Profits from the variation in the cable losses (*Profit1*) given by:

$$Profit1 = \sum_{j=1}^{n} \left\{ \left[R\,[k,i]\,\left(I1_j\,[k,i]\right)^2 - R\,[k,i]\,\left(I2_j\,[k,i]\right)^2 \right] t_j €_j \right\} * d * m. \tag{13}$$

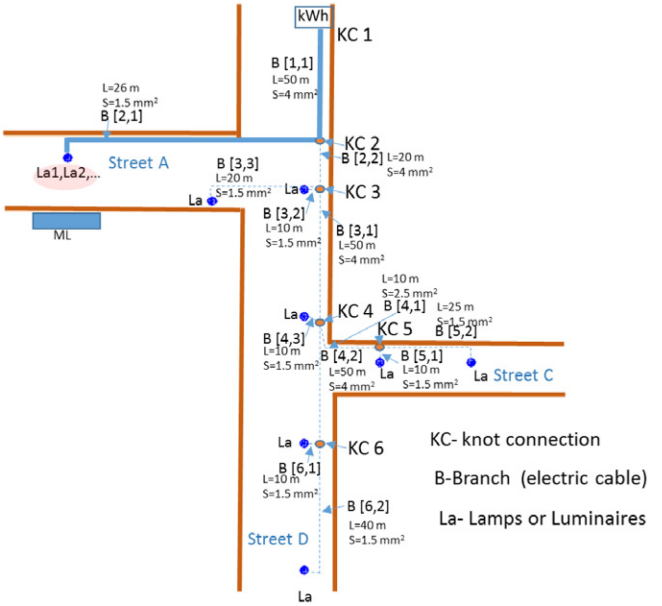

Fig. 2. Scheme of the installation.

- Profits from the variation in the power lamp (*Profit2*) given by:

$$Profit2 = \sum_{j=1}^{n} \left(\left(P1_j\,[k,i] - P2_j\,[k,i] \right) t_j €_j \right) * d * m. \tag{14}$$

- Total profits, given by:

$$\mathrm{R} = Profit1 + Profit2. \tag{15}$$

3. Economic evaluation

The rational selection of a solution to be taken during an investment decision should be based on a number of comparisons and analyses. The methods can be grouped into the following categories.

• Static methods are applied for the assessment of the efficiency during the initial stage when the economic justification of an investment is examined. One of the most popular methods involves the payback period. Simple payback period (SPP) refers to a method that enables one to determine the overall period necessary for the expenditure to repay its cost and is expressed as the length of time needed before an investment makes enough to recoup the initial investment.

$$\mathrm{SPP} = \frac{N_i}{O_i} \tag{16}$$

where:

N_i—initial investment,
O_i—mean annual savings resulting from an investment in €.

• Dynamic methods result in the verification of the credibility of the calculations due to the application of a discount, taking into consideration the change in the time value of money and the total cash flow associated with an investment.

The following methods have been found to have the most extensive application: net present/actual value *VAL*, internal rate of return *IRR* and payback period *PP*.

In this work, the net present value *VAL* or payback period *PP* is used, which is computed from the sum of the annual cash flows for a given annual interest rate.

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   ************************************************
   ************************************************
   ***                                          ***
   ***        CHOICE OF EFFICIENT LIGHTING      ***
   ***                                          ***
   ************************************************
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      TECHNOLOGY OF INITIAL LIGHTING:
Power loss in cables:5.915070Euro/Year


        WITH EFFICIENT Lamp1:
Power loss in cables:4.240115Euro/Year
VAL (present net value - WITHOUT LOSSES):402.013
VAL (present net value - WITH LOSSES)411.824

PP (Payback Period  - WITHOUT LOSSES):1.158312 Year
PP (Payback Period  - WITH LOSSES):1.134711 Year


        WITH EFFICIENT  Lamp2:
Power loss in cables:4.658358Euro/Year
VAL (present net value - WITHOUT LOSSES):292.067
VAL (present net value - WITH LOSSES)299.427

PP (Payback Period  - WITHOUT LOSSES):0.917672 Year
PP (Payback Period  - WITH LOSSES):0.897699 Year

      THE BEST INVESTMENT IS:

          Lamp:1


   WITH VAL(present net value):411.824
```

Fig. 3. Results of the software application.

The interest rate is indicated by the investor according to the desired profitability.

$$\mathrm{VAL} = \sum_{k=0}^{n} \frac{R_k - D_k - \mathrm{Inv}_k}{(1+a)^k} + \frac{V}{(1+a)^n} \tag{17}$$

with:

R—Net profit
D—Operation cost
Inv—New investment
n—Years of useful life
V—Residual value for the old equipment
a—Annual interest rate.

The payback period (PP) for the investment can be calculated using the following equation (Kostic and Djokic, 2009):

$$\mathrm{PP} = \ln \frac{100\,\mathrm{R}}{100\,\mathrm{R} - a\,\mathrm{Inv}} \div \ln \frac{100 + a}{100}. \tag{18}$$

4. Software application

The software is based on and developed in Pascal, and consists of structured matrices and vectors that allow the characterization of every street lamppost, luminaire and respective load in lighting circuits. The load diagram and parameters of the installation are entered via the keyboard and may, in future, conduct data acquisition automatically. After the lighting circuits have been characterized (physical parameters, load parameters, operating parameters), it begins by updating the data in all the sections, starting with the knot connections that do not feed other knot connections, the diagram loads being the set of outputs regarded as the diagram loads of the branch of the knot connection that feeds.

The software allows the introduction of multiple possibilities analysis, allowing the user to choose the analysis of a specific individual point of light, replace the existing technology on a street or in a selected group of streets or replace or control all the luminaires installed simultaneously, undertake investment analyses and advise more efficiently whether this can be chosen or not by the network lighting operator. The analysis is performed for all the selected settings and introduced into the software.

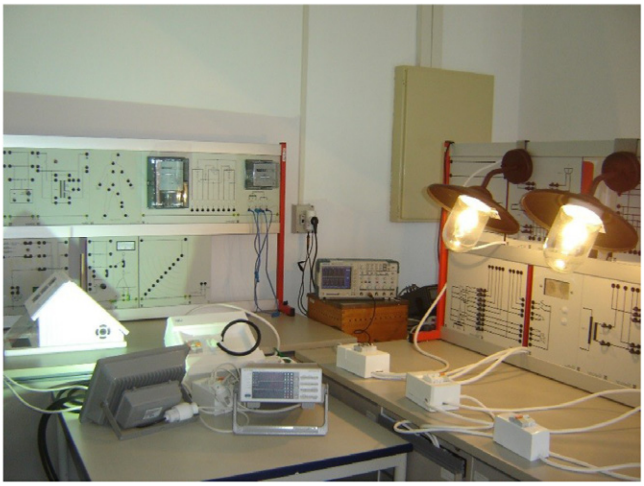

Fig. 4. Experimental setup.

These analyses are accomplished by the initial knot connection, the diagram load seen by the power provider being the overlapping of the diagram load of the branch.

5. Case study

5.1. Simulation results

As an example of verification and validation, a study was conducted to simulate the installation shown in Fig. 2, considering that the branch B[2, 1] feeds a spotlight to illuminate a building's facade. The objective will be to replace this with a more efficient spotlight (LED) including in the analysis the losses in the conductor sections.

Fig. 3 presents the results of the new software application to the scheme of Fig. 2. The results compare an initial situation, in branch B[2, 1], with one spotlight and halogen lamp of 240 W, with a spotlight LED of 30 W (€ 90) and another spotlight and fluorescent compact lamp of 96 W (€ 10), equivalent in terms of lighting.

5.2. Experimental results

The experimental set-up can be seen in Fig. 4.

Laboratory measurements were performed at the beginning and end of the cables identified in bold in Fig. 2. With the 240 W spotlight, 9.4 W losses in cable of B[1, 1] were obtained. In cable of B[2, 1], 0.6 W losses were obtained.

With the spotlight LED of 30 W (option 1), 5.8 W losses were obtained in cable of B[1, 1], and in cable of B[2, 1], 0.03 W losses were obtained.

Fig. 5 represents the measurements taken in the laboratory in cable of B[1, 1], affected by the substitution (option 1 more efficient).

The experimental results were analysed based on the initial situation and the cost-effective option (option 1 more efficient) indicated in the simulation results, during one year of operation and with a price of € 0.10/kWh, considered normal on average in street lighting.

From the experimental results, it was observed that the initial losses were equal to 10 W (9.4 + 0.6), while the losses for option 1 were equal to 5.83 W (5.8 + 0.03). Thus, the reduction of losses is equal to 41%, which is significant.

Fig. 5. Measure in the branch (cable) [1, 1], option 1 (end).

6. Conclusions

The paper presented software support and experimental results for choosing luminaires and control systems for street lighting installations, in cases of new or totally/partially remodelled projects, or an individual spotlight. It can be concluded that the losses in street lighting installations, although small, are not null and can make a considerable difference in the economic evaluation, supporting the investment decision. The results presented confirm that the payback period *PP* is lower and the net present/actual value *VAL* is superior when the losses are included, and may even turn from negative to positive, thus validating our study with simulation and experimental results. The use of software to support the designer allows the project to remake lighting installations for streets by analysing and choosing effective solutions, thus avoiding the use of technologies and experiences from which there is no certainty of economic profitability. It also allows the reduction of energy consumption by increasing the efficiency of lighting systems. The analysis and classification of energy efficiency in lighting systems for streets should include the whole life cycle and all the components of the system.

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