ON THE IMPACT OF SAFETY REQUIREMENTS, ENERGY PRICES AND INVESTMENT COSTS IN STREET LIGHTING REFURBISHMENT DESIGN

Beccali M.[1], Bonomolo M.[1], Leccese F.[2], Lista D.[2], Salvadori G.[2]

1- DEIM, Dept. of Energy, Information Engineering and Mathematics Modelling – University of Palermo, Viale delle Scienze Ed. 9, Palermo, Italy.

2- DESTEC, Dept. of Energy, Systems, Territory and Constructions Engineering – University of Pisa, Largo Lucio Lazzarino, Pisa, Italy.

ABSTRACT

Street lighting is an indispensable feature for the night landscape of cities. It is important for road safety, users visual comfort, crime prevention and to augment the perceived personal safety. Realize and maintain an adequate street lighting service is very expensive for municipalities with significant impact on their budgets. For this reason, special attention should be paid to the design of new street lighting systems and to the refurbishment of existing ones, since many of them are inadequate. In light of this it is very important to implement street lighting designs that fulfil lighting requirements avoiding energy waste and light pollution and, at the same time, result economically sustainable for municipalities. In this paper, an original step by step methodology for the lighting, energy and economic analysis of street lighting refurbishment designs has been introduced and explained in detail. The methodology is suitable for use in cities of different sizes. As an applicative example, the methodology has been tested in the town of Pontedera (Italy) and the results are discussed, also providing a sensitivity analysis of the economic feasibility with respect to the variations of electricity prices and investment costs.

KEYWORDS: Street Lighting; Lighting refurbishment design; Energy efficiency; Lighting design economic feasibility; CO_2 emission reduction; Lighting simulation.

1. INTRODUCTION

Street lighting is very important for the urban night-time panorama because has the potential for improving the appearance of an urban environment and it helps in increasing the attractiveness of a city [1]. A well designed lighting system can guarantee an adequate comfort level and facilitate the use of the city, improving the quality of life for the citizens and avoiding over-illumination and light pollution [2]. It is important for crime prevention, for property and goods safety, for night-time orientation and obstacle avoidance [3]. Lighting is also important because reduce the fear of crime and darkness with an augmentation of the perceived personal safety [3, 4]. It is also proven that adequate lighting can reduce road accidents, allowing vehicles to proceed safely and providing visibility at a greater distance so that evasive action can be taken in good time without the risk of abrupt manoeuvres [5]. Light with a high Colour Rendering Index (CRI) and an appropriate colour temperature can enable a better vision, improving people visual comfort [6, 7]. Public lighting service has relevant costs: electricity consumption for urban lighting is often a very important share of the economic budget of municipalities, apart for environmental impacts of electricity uses and the possible contribution to light pollution [8−11]. In order to quantify the problem, it should be noted that public lighting (predominantly street lighting) contributes for 3% to the worldwide electricity consumption [12]. In 2005, in Europe, road lighting consumed approximately 35 TWh and the costs are generally charged to municipalities [13]. In 2010, in the Netherlands, about 0.8 TWh per year were used by municipalities for public lighting, accounting for 60% of the local government's electricity consumption [4]. In the same year, in Italy, public lighting affects for the 12% the electricity consumption (6.1 of 50.8 TWh/year) [14].

Nowadays, lighting design is not too often supported by optimal decision strategies as well because proposed methods and criteria are not so many. In general, they differ from each other with regard to the factors and parameters taken into account in design stages and in the main aims. There are a number of studies which address the issue of lighting systems refurbishment in literature. Many studies describe refurbishment designs aimed at electricity consumption minimization, linked to the fulfilment of lighting requirements, but do not consider how to achieve them from an economic point of view [9, 15−17]. Other studies, although including simplified analysis of energy and economic feasibilities to refurbishment, are again focused on the respect of minimum safety lighting performance [10, 18]. It is important to know existing methodologies and studies to select the strategies most appropriate. Among the most recent studies Beccali et al. [18] presented a set of planning options applying them for a case study. Authors studied different retrofit actions to be applied in the specific case study and for each one they did an economic analysis. They found the most efficient action in terms of economy and efficiency but maintaining the comfort conditions. Filiminova et al. [19] studied the matters of Smart Grid concept implementation within outdoor lighting systems. As well these authors evaluated the payback period of the refurbishment design of the outdoor lighting system of a university campus in Russia based on LEDs, which feature enhanced operational reliability. The approach of Djuretic and Kostic [20] was based on the comparison of equal photopic or mesopic luminance levels. Moreover, they developed a new approach where energy efficiency indicators of LED luminaires in both the standard and reduced lighting regimes are taken into account. It was able to determine the potential energy saving in various dimming scenarios. Shahzad et al. [21] focused their attention on the sustainability of the project to find the greenest solution to fulfil the outdoor lighting requirements. To do this, they included an ecological impact assessment of commonly available lighting technologies, such as high pressure sodium lamps, compact fluorescent lamps and LEDs, by using Sustainable Process Index methodology. Carli et al. [22] developed a multi-criteria decision making tool to support the public decision maker in optimizing energy retrofit interventions on existing public street lighting systems. The aim is to simultaneously reduce energy consumption, maintain comfort, protect the environment, and optimize the distribution of actions in subsystems, while ensuring an efficient use of public funds. They applied and validate this method to a real street lighting system of a wide urban area in Bari (Italy). Peña-García [23] presented a work that is mainly focused on tunnels, showing and analysing some factors directly related to well-being that are highly influenced by the lighting and visual conditions. The author considered the psychological factors that can affect drivers and other factors related with the human visual system.

Since the lighting requirements are function of the traffic volume in each road, according to [5], the correct evaluation of this parameter becomes a key element in refurbishment designs for street lighting. Many often, actual traffic data are not available, for this reason, forecast models for traffic estimation aimed at the determination of the lighting requirements are welcome. In general, it is therefore indispensable to define a methodological approach that leads to a balanced design which considers performance requirements, energy efficiency and the economic costs (installation and maintenance costs of refurbished lighting systems). Currently, such type of approach is not yet available in technical standards and not completely shared by the scientific community. In this study, an original step by step methodology for the overall evaluation of street lighting refurbishment is proposed. In particular, the methodology uses two different approaches for the evaluation of the traffic volume in each road. The first one is based on an analysis of measured traffic data while the second one is based on a space syntax approach. In addition, this study provides a sensitivity analysis of economic performances of a case study, which considers the impacts of variation of energy and investment costs. Before illustrating the proposed methodology (Sec. 2) and its application to the case study of Pontedera town (Sec. 3), the present conditions of the Italian public lighting service are analysed in order to justify the need of refurbishments. Moreover, the major current regulations in the field of street lighting design and requirements in terms of energy efficiency of these systems are summarized.

1.1 Italian public lighting state of art

Italian urban and street lighting systems are for the most part old, obsolete and inefficient, often not complying with law requirements [16]. An ENEA study, from seven years ago, highlighted the superficiality of municipalities and other public administrations in addressing the issue of energy savings and of lighting systems design [24]. The study revealed that Italian public lighting systems are oversized by 3–4 times the actual requirements, are lacking adequate planning, produce significant light pollution, have no dimmable systems.

Up today, street lighting systems refurbishment still represents for Italian municipalities a big potential source of saving in terms of energy efficiency, CO_2 reduction and public money savings [16, 24]. Statistics show the presence of one luminaire every 6 inhabitants, so it is estimated that there are 10 million of luminaires in Italy [25]. Per capita annual consumption for public lighting in Italy is 107 kWh, more than twice the German (50 kWh) or United Kingdom (42 kWh), the two most virtuous countries at European level (in Europe per capita consumption is 51 kWh) [26]. Such consumption, in Italy, corresponds to a per capita spending of 18.7 €/year [27]. This relevant expense is about 2 billion euros a year and mainly affects the finances of municipalities [24]. Lamp source most utilized for road lighting in Italy is still high-pressure sodium with a nominal power of 150 W. In others European Countries the most common sources are characterized by a most frequent nominal power of 70 W, which would also be sufficient to comply with Italian laws (derived from European and international regulations) [26]. Figure 1 shows a comparison among the numbers of per capita installed luminaires for some Italian municipalities of different sizes: metropolises with more than one million of inhabitants (i.e. Roma, Milano, Torino), cities with about one hundred thousand inhabitants (i.e. Novara, Pisa), towns with less than fifty thousand inhabitants (i.e. Pontedera, Biella, Frosinone). From Figure 1 it is possible to notice how the number of pro capita luminaires decreases with the dimensions of the municipality. Pontedera –adopted in this paper as case of study– is characterized by a number of per capita installed luminaires of 6.0 [26]. As can be observed in Figure 2, for a restricted sample of Italian municipalities, the annual cost per luminaire (annual average all-inclusive cost) is fairly high [24, 26, 28], with variation from 290 €/year (Rome metropolis) to 139 €/year (Pontedera town). Despite the differences in the annual cost per luminaire, the per capita annual cost of public lighting is very similar for all the cities (see Figure 2). For example, the city of Rome has a per capita annual cost of 19 €, while Pontedera of 20 € [27]. In Table 1 the acceptable or best practice annual costs for public lighting service per luminaire, according to [26], are summarized. From the comparison between the values shown in Figure 2 and those shown in Table 3, it is evident that also for Pontedera (which has the lowest annual cost per luminaire, 139 €/year) there is ample margin of improvement towards the best practice.

It seems obvious how in Italy the design of public lighting systems is often overlooked or unsuitably carried out, hence the need to define a methodology to guide the designers toward appropriate refurbishment interventions. The methodology should be able to be applied to as many municipalities as possible and to guarantee the compliance with safety standards as stated by current regulations. At the same time, it should accomplish the goal of reduction in electricity consumption and so improve the environmental impact of lighting systems. Finally, the economic feasibility of refurbishment should be assessed in the light of the economic contexts of municipalities.

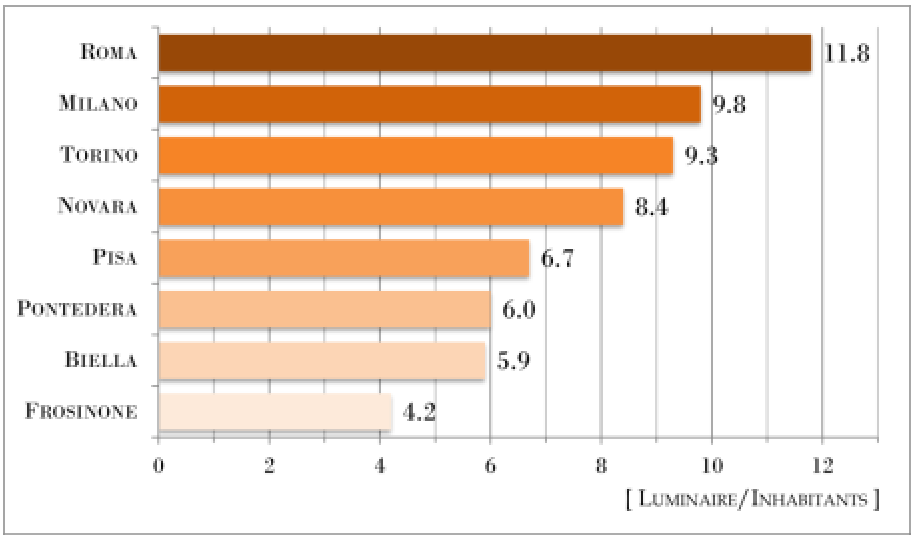


Figure 1. Comparison of per capita installed luminaires for some Italian municipalities.

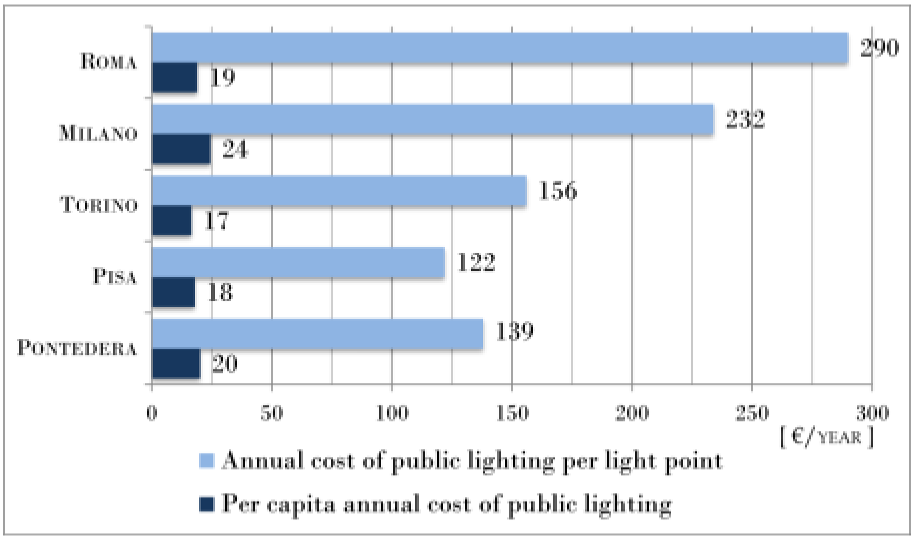


Figure 2. Comparison of annual per capita costs due to public lighting service and annual costs per installed luminaire for some Italian municipalities.

		Average installed power [W]	Costs		
			Energy [€/year]	Maintenance [€/year]	Total [€/year]
Municipalities with more than 100 000 inhabitants	Acceptable	130	123.7	42.4	166.0
	Best	110	104.6	24.2	128.9
Municipalities from 10 000 to 100 000 inhabitants	Acceptable	110	104.6	30.3	134.9
	Best	100	95.1	24.2	119.3
Municipalities up to 10 000 inhabitants	Acceptable	95	90.4	30.3	120.6
	Best	85	80.9	24.2	105.1

Table 1. Acceptable or best practice annual costs per installed luminaire for public lighting in Italy [26].

1.2 Current regulations

Road lighting design must be carried out in accordance with current regulations, which set minimum requirements and safety standards. Currently, at international level, it is in force the CIE 115 recommendation [5], at European level the EN 13201 standards [29–33] and at Italian level the UNI 11248 standard [34]. Such regulations provide for a breakdown into classes of roads and for every class, they identify a series of lighting requirements. Briefly, lighting systems must meet the following requirements [8, 35, 36]:

- to use devices that do not emit light upward to reduce light pollution;
- to do not over light, so illuminate the minimum required by the regulations;
- to reduce the number of luminaires and reduce the installed power;
- to use efficient sources, such as LEDs or low-pressure sodium lamps;
- to adapt light according to environmental and traffic conditions;
- to select lighting sources characterized by adequate values of CRI and colour temperature.

For an evaluation of the energy efficiency of road lighting systems, it is possible to refer to a set of energy performance indicators defined by regulations. In particular, the power density indicator (D_P) and the annual energy consumption indicator (D_E) have been introduced by EN 13201-5 [33]. The Lighting system Energy Efficiency Indicator (IPEI) and the Luminaire Energy Efficiency Indicator (IPEA) have been introduced by the local regulation of Emilia-Romagna Region. It represents a useful tool for energy classification of lighting systems and of street lighting luminaires [37].

2. METHODOLOGICAL APPROACH

The refurbishment design of street lighting must be developed using a best practice approach. The main goal must be to guarantee the minimum safety requirements according to traffic classes and area uses included in current regulations. Moreover, such design has to fulfil at least the following aims: minimize energy waste and related CO_2 emissions and to have an affordable economic impact. In order to assess these several aspects, a three phases method has been adopted and is here presented. Project performances have been evaluated using several parameters included in three sets:

- lighting parameters related to safety and visual comfort tasks;
- energy and environmental parameters;
- economic parameters.

The lighting parameters set consists of indices for assessing the minimum lighting requirements given by regulations. Compliance with these requirements guarantees the deployment of the minimum safety standards for road users. These requirements are identified according to road lighting classes. For this reason, they are strictly related to the lighting classes selection procedure based on several parameters given by standards (see Annex A). Among the various parameters to be determined for each road area of the city, surely the road traffic volume is the most difficult to be evaluated. In general, road traffic volumes are estimated or measured by traffic observation. A traffic observation campaign allows recollection of very precise traffic data, but it is a very expensive business in terms of time. A valid alternative for traffic volume determination is the use of the space syntax analysis (see Annex B), that guarantees high accuracy in traffic forecasting, as shown in [38–41].

Energy and environmental parameters are made up of a set of energy performance indicators and are used for evaluation of refurbishment improvements. For example, D_P, D_E, IPEI and IPEA indicators can be used. In addition, to assess the reduction of the environmental impact accomplished by the refurbished lighting systems, avoided equivalent CO_2 emissions can be estimated. CO_2 emissions in atmosphere per year (E_{CO_2}, g_{CO_2}/year) are calculated as the product between electrical energy consumption (E_L, kWh/year) and an emission factor (F_E, g_{CO_2}/kWh). The factor F_E, equal to 328 g_{CO_2}/kWh, has been deduced from the Italian Institute for Environmental Protection and Research (ISPRA) annual report [42]. Economic parameters are made up of the simple payback time of the investments needed for the refurbishment.

The methodological approach is structured in three phases (see Figure 3):

- Phase I. Analysis of public street lighting present conditions;
- Phase II. Refurbishment design;
- Phase III. Economic feasibility analysis of interventions.

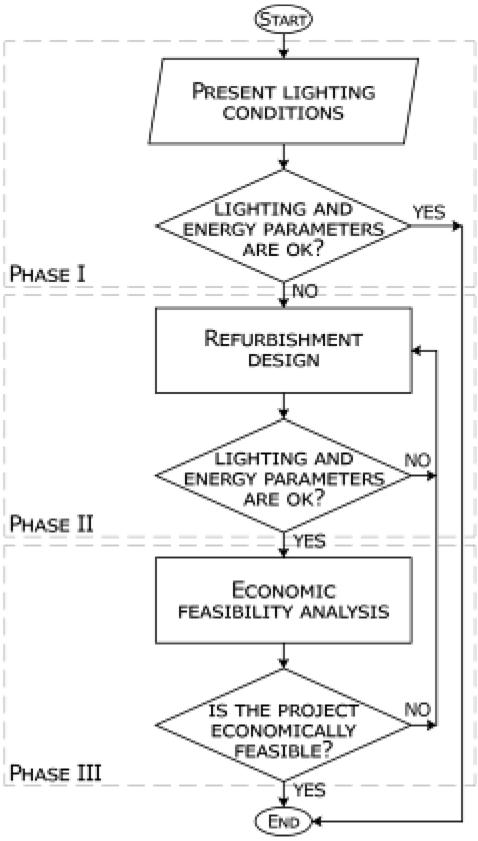


Figure 3. Flow-chart of the logical process leading to the lighting refurbishment of municipalities.

In Phase I, road lighting conditions are analysed and assumed as the input data of the forthcoming phases. Present lighting conditions are analysed by evaluating whether or not they respect lighting and energy parameters. If criteria for minimum safety requirements are not respected and/or lighting systems appear old or energetically inefficient, then it is possible to go to Phase II.

In Phase II, through a lighting design, lighting requirements problems are solved and/or lighting systems energy efficiency is improved. Lighting design is analysed again by evaluating whether or not lighting systems respect lighting and energy parameters.

In Phase III, the economic feasibility of the proposed interventions is analysed with an evaluation of the payback time period of the needed investments. If lighting design is not sustainable, a new lighting design formulation is necessary and the logical process must be repeated from Phase II. In the following sub-sections, each phase will be further discussed and analysed.

2.1. Analysis of public street lighting present conditions (Phase I)

Application of Phase I of the methodology has been divided into several steps which are summarized below (see Figure 4):

I.1. Survey of the characteristics of roads and of existing lighting systems;
I.2. In situ lighting measurements or software simulation;
I.3. Minimum safety requirements assessment;
I.4. Energy efficiency of lighting systems assessment;
I.5. Minimum safety requirements check;
I.6. Energy efficiency of lighting systems check.

Phase I can be distinguished in two sub-phases, in the first one (Steps from I.1 to I.4) all the necessary data are collected while in the second one (Steps I.5 and I.6) an analysis of present lighting conditions is carried out.

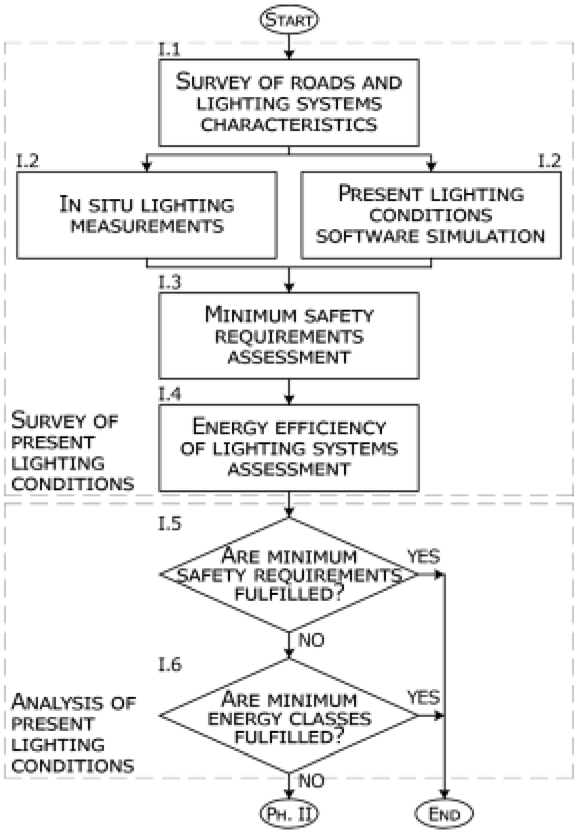


Figure 4. Flow-chart of the analysis of public street lighting state of art (Phase I).

After the definition of the area to be examined, first Step (I.1) concerns the survey of road geometric features and of road lighting systems features.

Road geometric features are: total length of the road, number and type of road areas (carriageways, bicycle lanes, sidewalks, conflict areas, parking lane, roadside green areas), width and height of areas, maximum allowed speed for vehicle lanes, etc.

Road lighting features are: identification of luminaire and lamp types (with their photometric data), identification of luminaire arrangements (one-sided, two-sided, two-sided staggered, etc.) and its dimensions (poles distance, poles height, distance from carriageway/sidewalk, luminaire tilt, etc.). The knowledge of the years of service and of maintenance cycles is also important for an evaluation of systems.

Step I.2 can be carried out following two different alternatives: a lighting measurements campaign or a software simulation of present lighting conditions. Lighting measurements and lighting parameters calculations have to be conducted, respectively, in accordance with EN 13201-4 and EN 13201-3.

In Step I.3 a reference standard has to be selected. In accordance with the adopted standard, lighting classes selection and minimum safety requirements have to be determined for every road area defined in Step I.1.

In Step I.4 the energy efficiency assessment is made through a set of energy performance indicators as stated by international and local standards. One of the goals is to calculate energy classes for luminaires and lighting systems. It must be reminded that the EN 13201-5 introduces two energy performance indicators: the power density indicator (D_P, $W \cdot lx^{-1} \cdot m^{-2}$) and the annual energy consumption indicator (D_E, $Wh \cdot m^{-2}$). Unfortunately, with such indicators, the energy performance of street lighting systems with different road geometries or different lighting requirements cannot be directly compared to each other. It is because the energy performance is influenced, among others, by the geometry of the area to be illuminated and the minimum lighting requirement. To overcome this issue, the Luminaire Energy Efficiency Indicator (IPEA) and the Lighting systems Energy Efficiency Indicator (IPEI) have been adopted. These two indicators (dimensionless) allow for a more robust assessment of the systems which leads toward a sort of energy classification (see Annex C).

In Step I.5 lighting parameters set is checked with a comparison between lighting parameters obtained in Step I.2 and minimum safety requirements obtained in Step I.3. The aim of this step is to understand which roads are not in compliance with standard requirements.

In Step I.6 energy and environmental parameters set is checked with a comparison between energy classes defined in Step I.4 and the minimum energy classes required by standards (see Annex C). If minimum safety requirements and minimum energy classes are fulfilled, luminaires and lighting systems can be considered suitable and the process ends. Conversely, implementation of Phase II of the methodology is required.

2.2. Refurbishment project (Phase II)

Phase II has been divided into several steps which are listed below (see Figure 5):

- II.1. Identification of objectives to be pursued during the design stage;
- II.2. Choice of the new luminaires to be adopted;
- II.3. Lighting design;
- II.4. Check of the overall energy efficiency of the new lighting systems.

Step II.1 concerns the identification of the objectives to be pursued during the design stage. Each design option must at least ensure compliance with minimum safety requirements in roads, improve the energy efficiency of lighting systems and luminaires and ensure an economic sustainability.

Step II.2 concerns the choice of the new luminaires. The choice of luminaire depends on several factors. One of this is related to its architectural design and its aesthetic integration in the city. Of course, it cannot be measured by any parameter in the proposed method. There are also important technical features to be considered such as light distribution (strictly related to height and distances of poles), colour rendering and, last but not least, energy efficiency and cost.

In Step II.3, through a lighting design, roads not in compliance with regulations in force have to be refurbished. In road refurbishment, design options requiring the lowest initial economic investment have priority. The choice is made in order to contain the necessary investments by municipalities in implementing the interventions and make the lighting design economically affordable. Therefore, the first design option is to replace the obsolete luminaires with new ones. If it is not possible to ensure compliance with the minimum safety requirements, the second design option is to modify luminaire arrangements with the consequence of increasing the initial economic investment of municipalities. To improve electrical energy savings a luminaire dimmable solution in different time bands has to be adopted. The subdivision in time bands is possible after an observation of traffic conditions at night-time of the examined area. The lighting class of every road area has to be re-calculated for each time band to see if the changed traffic conditions determine a decrease in the lighting class and so a reduction in the necessary luminous flux.

In Step II.4 the design options for the new lighting systems have to be evaluated through the energy performance indicators (D_P, D_E, IPEA and IPEI) and using a “best practice” approach. The chosen criterion has to comply at least with the following conditions: new luminaires must have IPEA class A^{++}, all the carriageways must meet the minimum acceptable energy class (see Annex C), minimum upgrade of D_P=45%, and minimum upgrade of D_E=30%. All design options and choices have to be checked according to the above mentioned conditions.

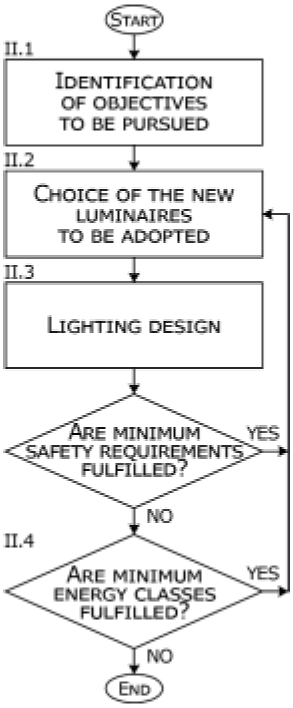


Figure 5. Flow-chart of the refurbishment design (Phase II).

2.3. Economic feasibility analysis of interventions (Phase III)

Phase III has been divided into several steps which are listed below (see Figure 6):

III.1. Assessment of economic value of the investments;
III.2. Calculation of economic savings;
III.3. Calculation of payback time of investments;
III.4. Analysis of payback time of investments (payback time sensitivity).

In Step III.1 the economic value of the investments necessary for the refurbishment design must be calculated. Investments can be estimated through detailed lists of materials, workmanship and present market prices.

In Step III.2 global annual savings have to be calculated as the difference between the costs at present and at the design status. Annual money savings are due to reduced electrical energy consumptions and to lower maintenance costs of the new lighting systems (see Annex D for their calculation).

In Step III.3, to evaluate the economic feasibility of the refurbishment interventions, their Simple Payback Times (SPT, year) must be evaluated (see Annex D). On the base of the SPT-years needed for refurbishment designs, municipalities can evaluate the feasibility of the investments. Investments with SPT values lower than 10 years can be considered favourable, with values lower than 15 years acceptable and with values higher than 20 years not convenient. In the last case a new design option must be found. Calculation of the payback times has been done by considering all the economic parameters to be constant. However, this is a strong assumption, in particular regarding the cost of electricity and the cost of LED luminaires.

In Step III.4 a sensitivity analysis can be made and the SPT can be recalculated considering reasonable variations and trends of these two costs. For both the variables, the variation range can be set to –20% and +20% from the central value. In this case, the result is a timeframe of years. The best case (low SPT value) will be for an increase of 20% of electricity bill and a decrease of 20% of LED luminaires cost, vice versa for the opposite case. Looking at the rising of Italian energy cost trends [43], and of the decreasing of LED luminaires cost [44, 45], it is reasonable to limit the previous timeframe, where LED luminaires cost can vary only from 0 to –20% and electricity cost from 0 to +20%. In this last case, a reduction in the range of payback periods is obtainable. These considerations make the investment for public street lighting refurbishment even more convenient.

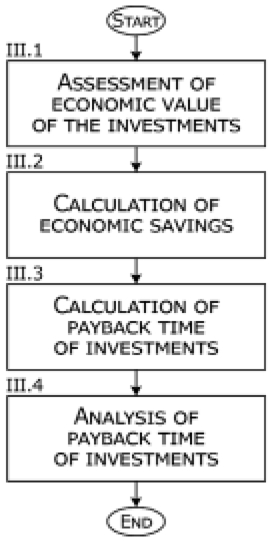


Figure 6. Flow-chart of the economic feasibility analysis of interventions (Phase III).

3. THE CASE STUDY OF PONTEDERA TOWN

In order to apply the methodological approach proposed in the previous section, the town of Pontedera has been chosen. Pontedera is a Tuscan town of medieval origin located in central Italy, 30 km far from Pisa (see Figure 7). The main urban nucleus of Pontedera is bordered by three rivers (the Era, the Arno and the Scolmatore) and two important infrastructures (the FI-PI-LI motorway connecting the cities of Florence, Pisa and Livorno and the Pisa-Florence railway). In the next sub-Sections, the steps provided for the different phases of the proposed methodology (see Section 2) are recalled and applied to the case study.

3.1. Survey of the characteristics of roads and of existing lighting systems (Phase I, Step I.1).

For Pontedera roads, geometric features have been summarized in tables as the one shown in the example of Table 2, together with the geometric data of the lighting installations. Luminaires and their photometric characteristics have been detected for every road in the main urban nucleus (counting about 2900 luminaires). In Table 3 an abacus with the main features of Pontedera luminaires is presented together with the main features of lamps. In Figure 8 a map with luminaire distribution is illustrated. It has emerged that the most common luminaire is F, installed in 34% of roads and equipped with high-pressure sodium, metal halide or high-pressure mercury lamps with powers between 100 and 250 W. In Figure 9 the power distribution of the lamps installed in Pontedera for public lighting service is illustrated. The most common lighting source is metal halide lamp and the most used nominal power is 150 W, while there are still highly polluting mercury vapour lamps (although low in percentage) and highly efficient LED sources are almost negligible (see Figure 10).

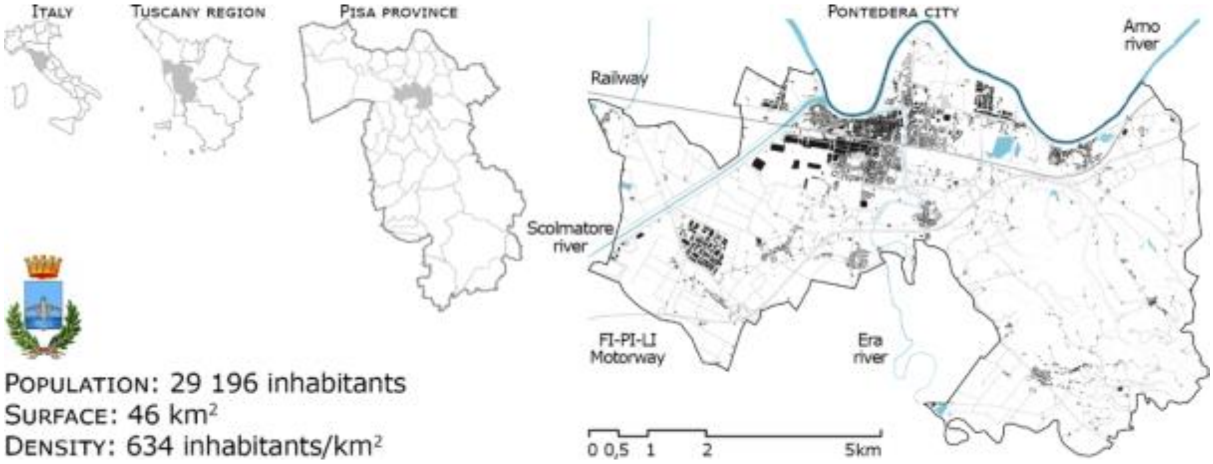


Figure 7. Location and essential data of Pontedera town.

3.2. In situ lighting measurements and software simulation (Phase I, Step I.2)

In this paper the approach of using a lighting software simulation has been chosen since it represents a much faster method, even continuing to ensure an adequate accuracy of the lighting simulations carried out [46, 47].

Simulations have been carried out on a sample group consisting of 40 roads (illustrated in Figure 11), chosen to be representative of Pontedera roads. The group of roads has been determined with the help of a space syntax analysis (see Annex B). The sample group has been defined after dividing all Pontedera roads into six groups. Each group is characterized by the following global integration index ($I_{[r=n]}$) range of values:

Group 1:	$2.48 \leq I_{[r=n]} \leq 2.16$	Group 2:	$2.16 < I_{[r=n]} \leq 1.84$
Group 3:	$1.84 < I_{[r=n]} \leq 1.52$	Group 4:	$1.52 < I_{[r=n]} \leq 1.20$
Group 5:	$1.20 < I_{[r=n]} \leq 0.88$	Group 6:	$0.88 < I_{[r=n]} \leq 0.56$

For each group, the same percentage of roads has been chosen. Selected roads are representative of all luminaires installed in Pontedera. Every road simulation has been carried out with the help of DIALux software [48] by modelling road geometry and luminaires arrangements. Luminaires photometric data have been implemented in the software thanks to EULUMDAT photometric file. Given the absence of a municipal maintenance planning in Pontedera, simulations have been carried out by estimating maintenance factors according in CIE 154 recommendation [49].

As an example, Figure 12a shows the simulation of the luminance mapping for *Tosco-Romagnola* carriageway (see example in Table 2). Figures 12b and 12c show a true-colours and a false-colours rendering of the horizontal illuminance mapping on the same road surface. Software outputs have been verified with a comparison between simulated values and in situ measurements for some road of the sample. The percentage difference between measured and simulated values was always less than 15% and the simulated values appear to be cautionary respect in situ measured ones.

Tosco-Romagnola road [road length = 466 m]		
		
		
Luminaire (see Table 3)		F-2 B
Energy efficiency		
D_P indicator	42.64 mW/(lx·m^2)	
D_E indicator	2.75 kWh/m^2	
IPEA class	C E	F-2 B
IPEI class	F (sidewalk luminaire side) E (bicycle lane) C (carriageway)	
Geometric characteristics of installation		
Installation arrangement	one-sided one-sided	F-2 B
Luminaire mounting	head-pole mounting head-pole mounting	F-2 B
Tilt angle	15° 0°	F-2 B
Luminaire number	13 21	F-2 B
Luminaire distance	35.50 m 11.85 m	F-2 B
Geometric characteristics of supports		
Pole with F-2 luminaires	pole height	10.50 m
Pole with B luminaires	pole height	2.80 m
Lighting classes (CIE 115:2010)		
	Speed limit	50 km/h
Carriageway		M3
Conflict area		C3
Bicycle lane		P3
Sidewalk		P4

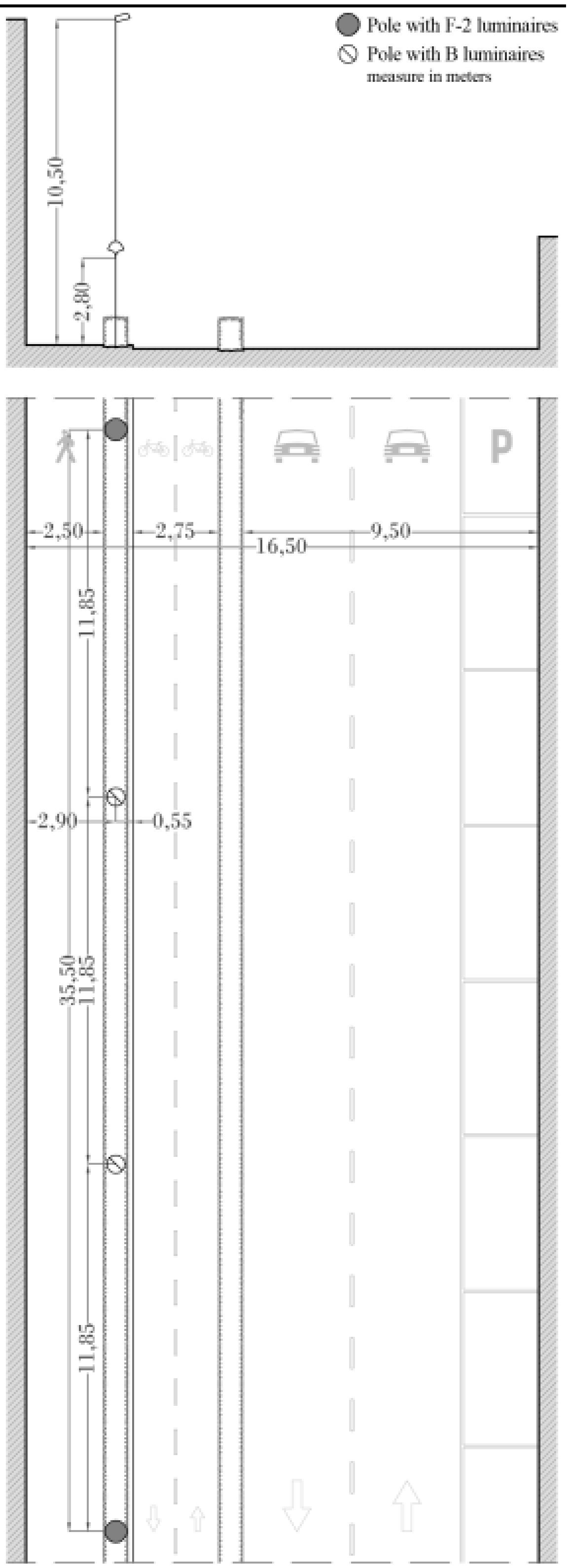


Table 2. Road geometric data and characteristics of lighting arrangements: the case of *Tosco-Romagnola* road.

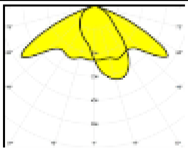
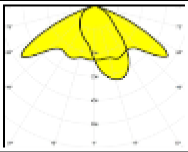
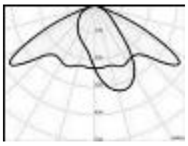
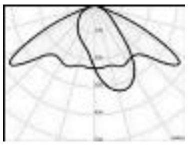
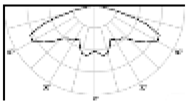
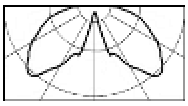
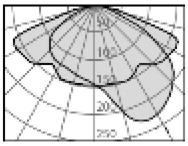
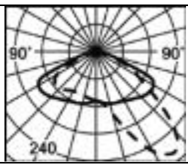
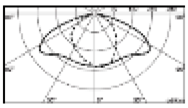
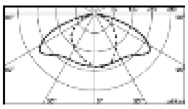
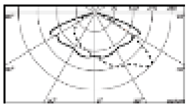
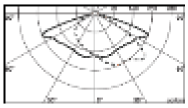
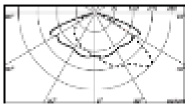
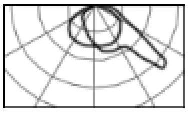
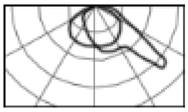
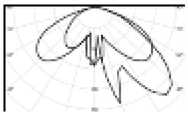
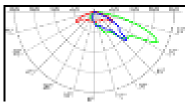
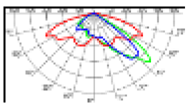
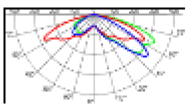
ID	Image	Photometry	Main features
A-1			P_{lum} 114 W ϕ_{lum} 7 546 lm η_{lum} 66 lm/W Source HPS T_c 2 000 K
A-2			P_{lum} 157 W ϕ_{lum} 11 543 lm η_{lum} 73 lm/W Source HPS T_c 2 000 K
A-3			P_{lum} 114 W ϕ_{lum} 6 700 lm η_{lum} 59 lm/W Source MH T_c 4 200 K
A-4			P_{lum} 169 W ϕ_{lum} 11 412 lm η_{lum} 68 lm/W Source MH T_c 3 000 K
B			P_{lum} 85 W ϕ_{lum} 4 019 lm η_{lum} 47 lm/W Source HPS T_c -
C			P_{lum} 116 W ϕ_{lum} 2 430 lm η_{lum} 21 lm/W Source HPS T_c 2 100 K
D			P_{lum} 158 W ϕ_{lum} 10 897 lm η_{lum} 69 lm/W Source MH T_c 3 000 K
E			P_{lum} 157 W ϕ_{lum} 9 988 lm η_{lum} 64 lm/W Source MH T_c 3 000 K
F-1			P_{lum} 118 W ϕ_{lum} 6 646 lm η_{lum} 56 lm/W Source HPS T_c 2 000 K
F-2			P_{lum} 166 W ϕ_{lum} 13 194 lm η_{lum} 79 lm/W Source HPS T_c 2 000 K
F-3			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
F-4			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
F-5			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
G-1			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
G-2			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
H			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
LED12			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
LED20			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K
LED50			P_{lum} 118 W ϕ_{lum} 6 099 lm η_{lum} 52 lm/W Source MH T_c 4 200 K

Table 3. Main features of the luminaires in Pontedera: ID code in the present study, luminaire picture, luminaire photometric diagram, luminaire technical data. (Legend: P_{lum}, Luminaire power; ϕ_{lum}, Luminaire luminous flux; η_{lum}, Luminaire efficacy; T_c, Colour temperature; HPS, High Pressure Sodium; MH, Metal Halide; HPM, High Pressure Mercury; LED, Light Emitting Diode).

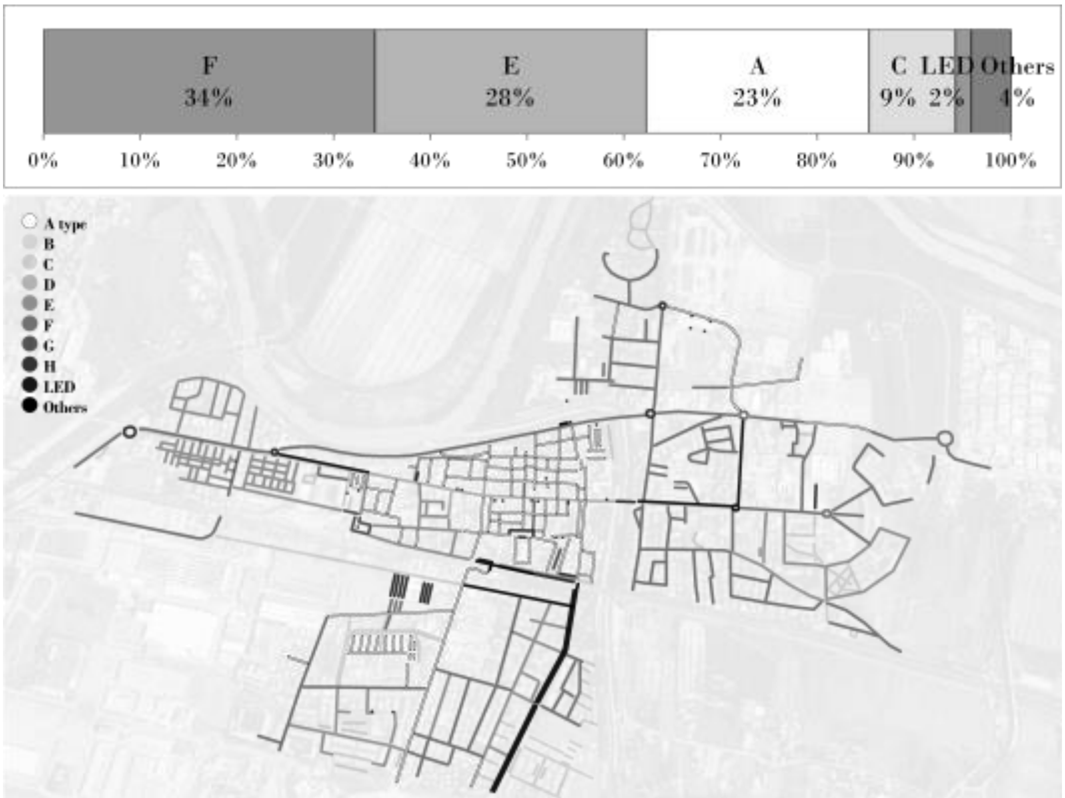


Figure 8. Percentage (top) and planimetric (bottom) distribution of luminaires installed in Pontedera for street lighting.

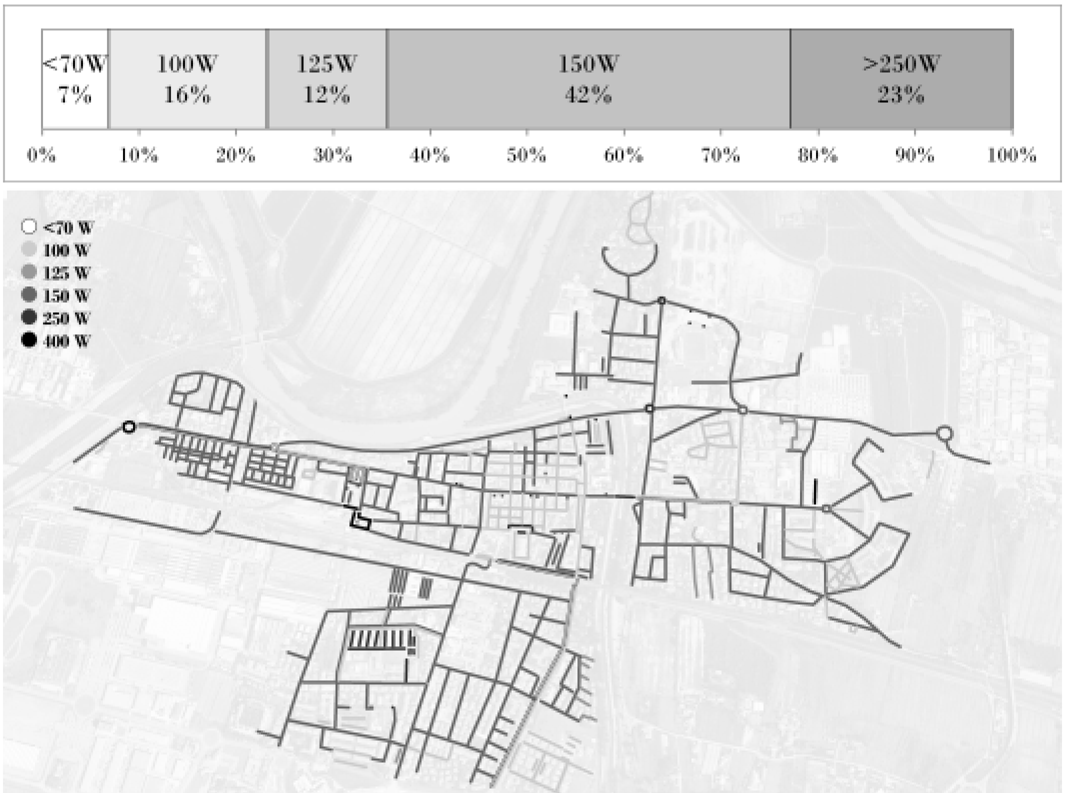


Figure 9. Percentage (top) and planimetric (bottom) distribution of the lamps nominal powers installed in Pontedera for street lighting.

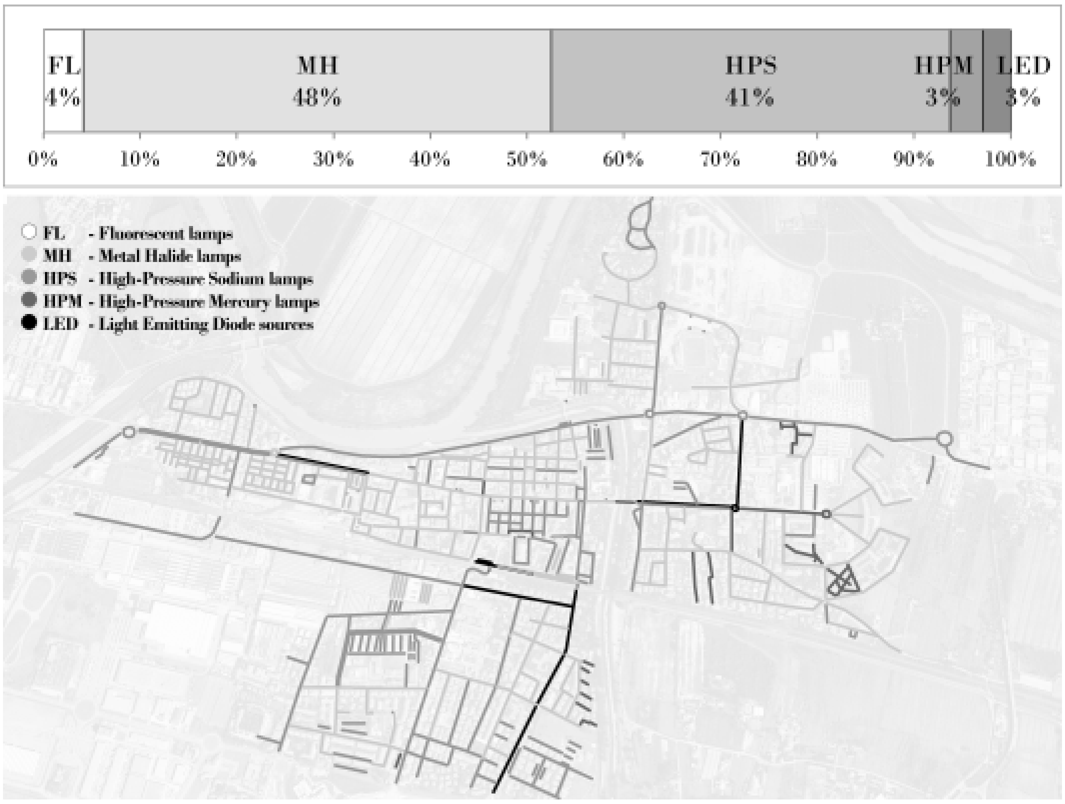


Figure 10. Percentage (top) and planimetric (bottom) distribution of the lamp types installed in Pontedera for street lighting.

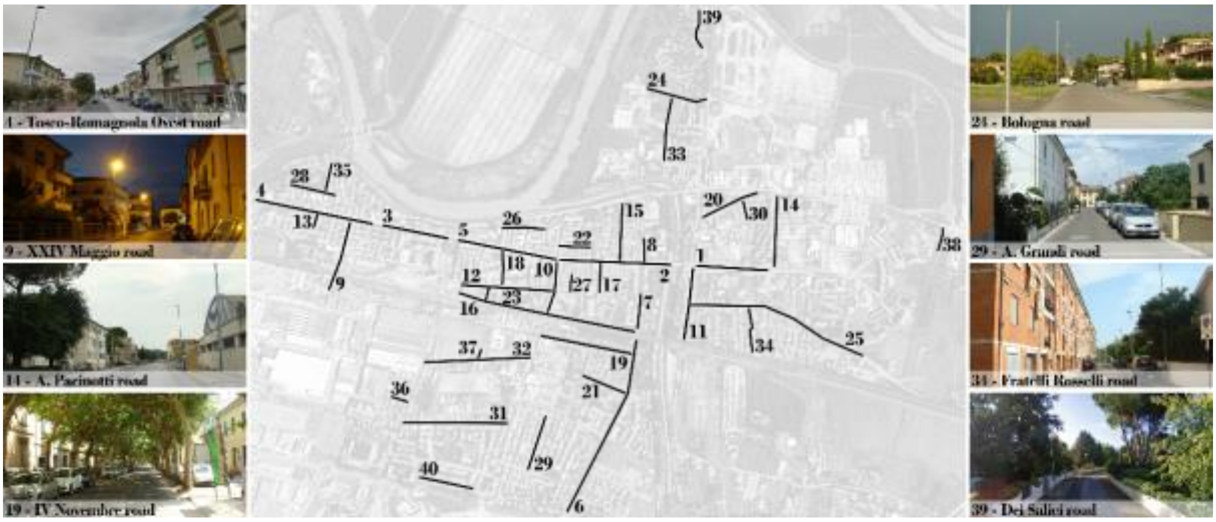


Figure 11. Location of the 40 sample roads of Pontedera town used for the lighting simulations.

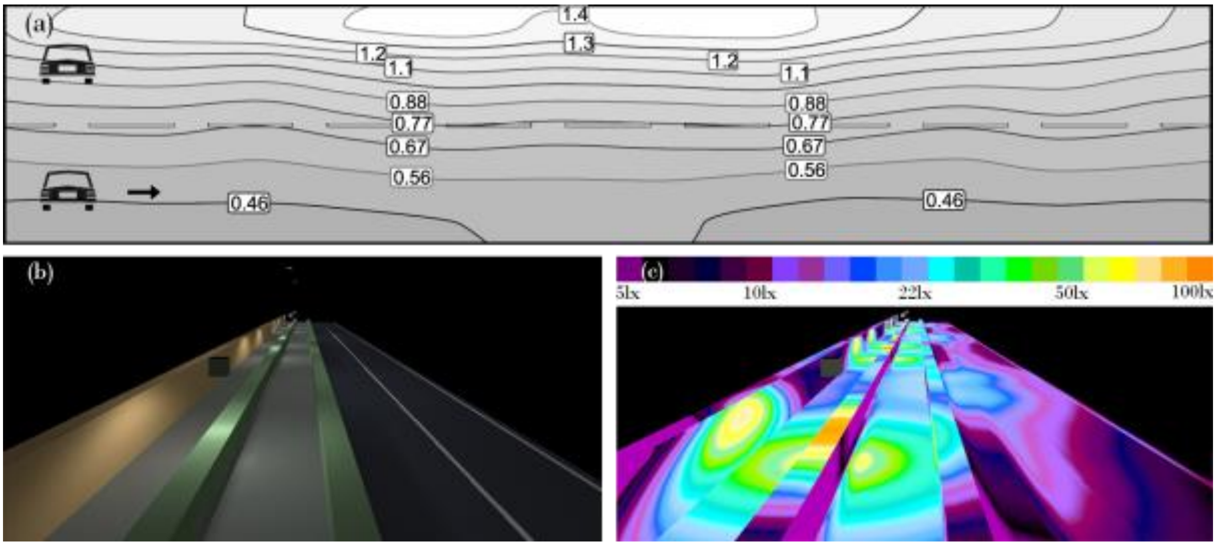


Figure 12. Examples for *Tosco-Romagnola* road software output (road example of Table 2): (a) luminance mapping (cd/m^2) for the carriageway; (b) and (c) true-colours and false-colours rendering of the horizontal illuminance mapping (lx).

3.3. Minimum safety requirements assessment (Phase I, Step I.3)

The CIE 115 has been chosen as the reference for the assessment of road minimum safety requirements. However, it should be noted that using the method suggested by other standards similar results can be achieved. In Table 4 the example for lighting classes selection of *Tosco-Romagnola* road is given. After lighting classes selection for every road area, minimum safety requirements are defined on the base of tables given by CIE 115 (see Annex A).

As already mentioned, for traffic volume determination, in this study a space syntax analysis has been used (see Annex B). Space syntax results have been tested with a comparison of traffic data obtained from a traffic observation campaign in the 40 examined roads. After the comparison with actual available data the analysis showed an accuracy of 94% in forecasting traffic volumes.

M lighting class parameters		$V_{w,M}$
Speed	Moderate	0.0
Traffic volume	Very high	1.0
Traffic compositions	Motorized only	0.0
Separation of carriageways	No	1.0
Intersection density	Moderate	0.0
Parked vehicles	Present	0.5
Ambient luminance	Moderate	0.0
Visual guidance / traffic control	Moderate or good	0.0
$6 - \sum V_{w,M} = 6 - 2.5 = 3.5 \approx 3 \rightarrow$ M3		

P lighting class parameters – bicycle lane		$V_{w,P}$
Speed	Low	1.0
Traffic volume	Very high	1.0
Traffic compositions	Cyclists only	0.0
Parked vehicles	Present	0.5
Ambient luminance	Moderate	0.0
Facial recognition	Not necessary	
$6 - \sum V_{w,P} = 6 - 2.5 = 3.5 \approx 3 \rightarrow$ P3		

C lighting class parameters		$V_{w,C}$
Speed	Moderate	1.0
Traffic volume	Very high	1.0
Traffic compositions	Motorized only	0.0
Separation of carriageways	No	1.0
Ambient luminance	Moderate	0.0
Visual guidance / traffic control	Moderate or good	0.0
$6 - \sum V_{w,C} = 6 - 3.0 = 3.0 \rightarrow$ C3		

P lighting class parameters		$V_{w,P}$
Speed	Very low	0.0
Traffic volume	Very high	1.0
Traffic compositions	Pedestrian only	0.0
Parked vehicles	Present	0.5
Ambient luminance	Moderate	0.0
Facial recognition	Necessary	
$6 - \sum V_{w,P} = 6 - 1.5 = 4.5 \approx 4 \rightarrow$ P4		

Table 4. Lighting classes selection (see Annex A) for *Tosco-Romagnola* road areas (see Table 2).

3.4. Energy efficiency of lighting systems assessment (Phase I, Step I.4)

Energy classes and performance indicators (D_P, D_E, IPEI and IPEA) have been calculated with the equations and tables shown in Annex C. Results are collected in the same tables of the geometric and lighting characteristics (see Table 2 for *Tosco-Romagnola* road example).

3.5. Minimum safety requirements check (Phase I, Step I.5)

As shown in Figure 13, minimum safety requirements check, carried out on the entire road sample, showed that only 32% of the roads meet all the minimum safety requirements prescribed by CIE 115, while in the remaining 68% of roads at least one requirement is not respected.

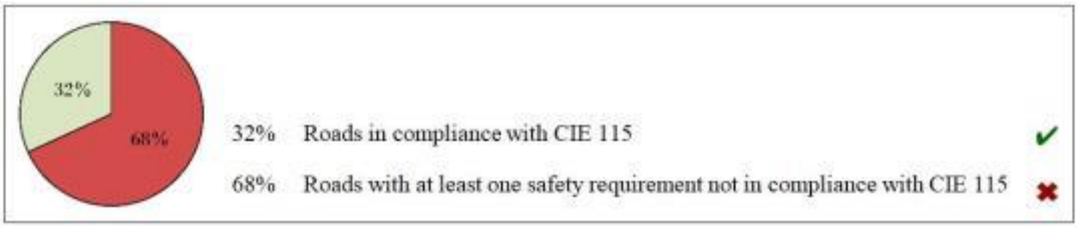


Figure 13. Minimum safety requirements check.

3.6. Energy efficiency of lighting systems check (Phase I, Step I.6)

The comparison between the simulation outputs values and the minimum safety requirement values revealed that 36% of the carriageways are not compliant with CIE 115, while the 32% of the remaining carriageways show an energy waste because the simulated luminance value exceeds the reference value one of more than 1.5 times (as shown in Figure 14a). Among the sidewalks placed on the opposite side of the luminaires, the 11% is not in compliance with CIE 115, the 72% show an energy waste and only the 17% have acceptable safety and energetic characteristics (as shown in Figure 14b). Among the sidewalks on the same luminaires side, all have the horizontal average illuminance value 1.5 times higher than the minimum required by the CIE 115 (see Figure 14c).

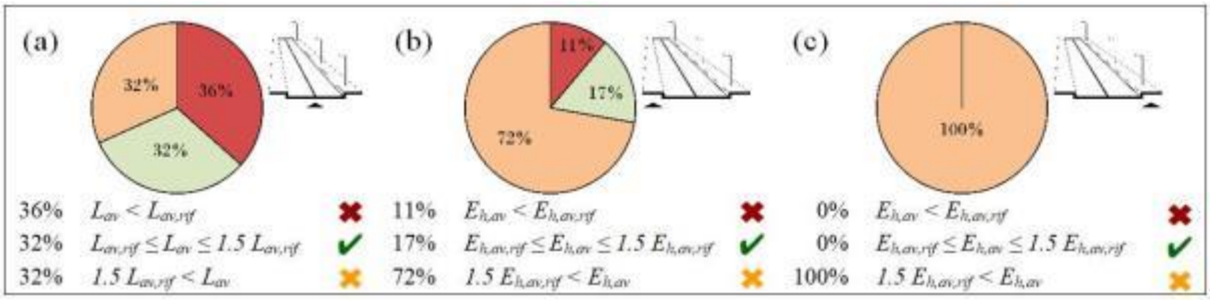


Figure 14. Energy waste of lighting systems: (a) percentage of carriageways with excessive luminance (L_{av}) values; (b) percentage of sidewalks placed on the opposite luminaires side with excessive average illuminance ($E_{h,av}$) values; (c) percentage of sidewalks placed on the same luminaires side with excessive average illuminance ($E_{h,av}$) values.

By the analysis of the energy performance indicators, it arose that only 27% of the roads have acceptable luminaires (IPEA class ≥C, IPEA value >0.93, see Annex C), while 73% of them are in the lower classes (58% of which in the last three energetic classes, see Figure 15a). The IPEI indicator must be calculated for every road area (carriageway – bicycle lane – sidewalks). To evaluate a road as a whole, the following classification has been proposed:

- roads with totally inadequate lighting systems (all road areas are in the worst class G);
- roads with inadequate lighting systems (all road areas are in a class lower than B);

– roads with adequate lighting systems (all road areas are in class B or higher).

According to this classification, it is worth noting that 21% of roads have all road areas in class G, 70% has at least one area in a class above the G but however below the B, while only 9% of roads is energetically acceptable (generally pedestrian roads, see Figure 15b).

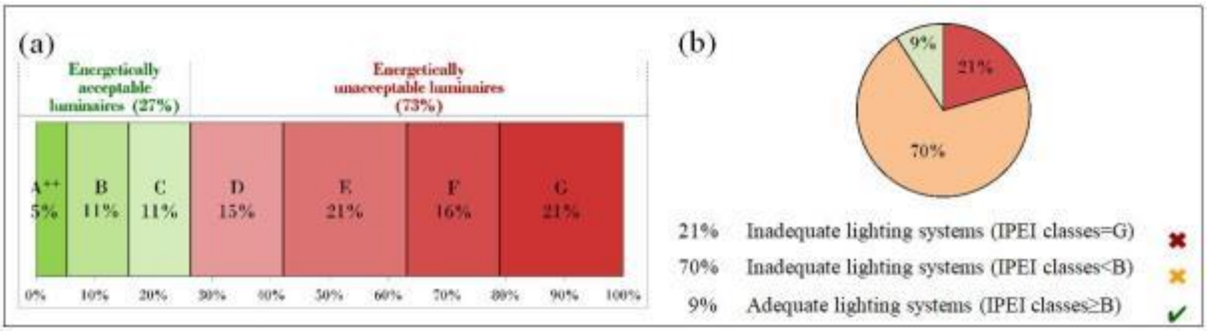


Figure 15. Energy efficiency of lighting systems: (a) percentage distribution of IPEA classes depending on roads of the study sample; (b) roads percentage depending on whether or not their lighting systems are energetically acceptable.

Regarding IPEI values for individual road areas, only 3% of the carriageways have an acceptable IPEI class (IPEI class ≥B, IPEI value <1.09, see Annex C). Among the sidewalks placed on the luminaires side only 10% have an IPEI class higher than or equal to B while 77% of them are in the worst energy class G. All sidewalks placed on the opposite side of luminaires do not prove to be energetically acceptable and even 94% of them are in G class, as shown in Figure 16. For the bicycle lanes of the sample, three are in class E and the fourth in class G.

At the end of the analysis of street lighting present conditions (Phase I, see sub-Sec. 2.1) of Pontedera town the following considerations can be summarized: the 70% of Pontedera's roads do not guarantee the minimum safety levels required by CIE 115 and the lighting systems appear old and energetically inefficient in 91% of roads. From these critical issues, the need to develop a refurbishment design for Pontedera street lighting is evident.

3.7. Identification of objectives to be pursued during the design stage (Phase II, Step II.1)

As for the present lighting conditions, the lighting design options will be analysed with the lighting and energy parameters sets. The lighting design that will be described intends to pursue the following objectives: ensure the compliance of minimum acceptable safety requirements in roads currently not respecting them; improve the energy efficiency of lighting systems and luminaires for a better environmental sustainability of them and select design options with good payback time.

3.8. Choice of the new luminaires to be adopted (Phase II, Step II.2)

The most important feature considered for the luminaires choice concerned their energy efficiency. All class A^{++} luminaires have been adopted in compliance with the conditions of sub-Sec. 2.2. Luminaires that use LED technology have been adopted. The advantages of adopting LED technology for public street lighting are mainly due to the reduction in electrical energy consumption and installed power, thanks to the high performances that those sources have now reached. Also, with the use of LEDs there is a reduction in maintenance costs due to their high lifetime. Among the many available on the market, different LED luminaires have been selected and adopted. The LED luminaires have the same photometric features but they are characterized by different electrical powers specified in the luminaire ID (see Tables 5 and 9). An example of selected luminaires is shown in Table 5. Eye-catching luminaires have been chosen, that can be seen in daylight hours as well as urban design elements. Properties related to their lighting distribution and quality have been handled in the further steps of the design process.

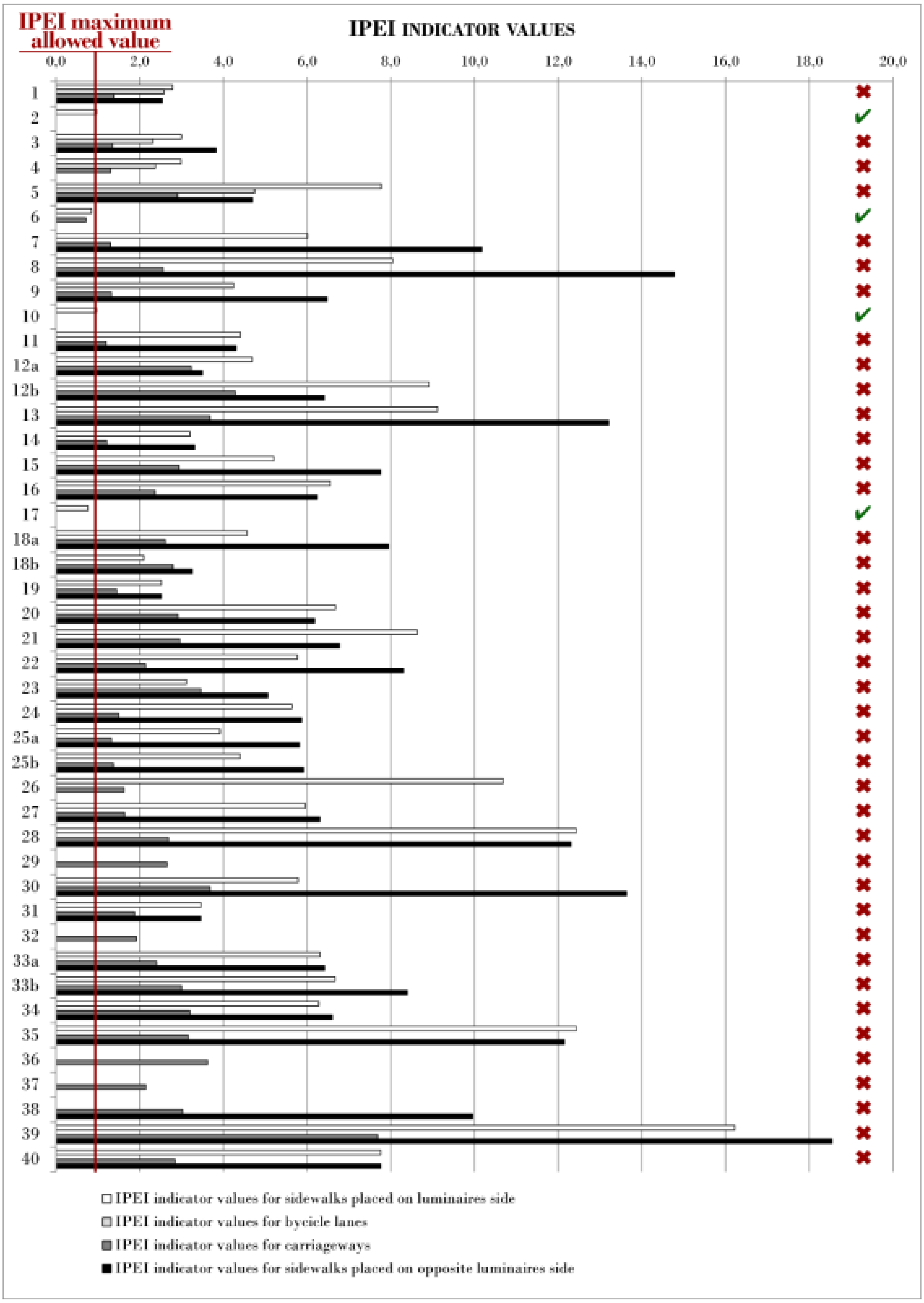


Figure 16. IPEI indicator values depending on the considered road area for the 40 sample roads.

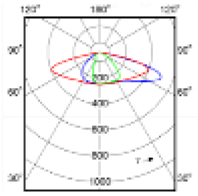
ID: PH138			
			
P_{lum}	138 W	Sources	64 LED
ϕ_{lum}	14 663 lm	T_c	4 000 K
η_{lum}	106 lm/W	CRI	>70

Table 5. Example of adopted luminaires for the refurbishment design: picture and main techinical features (the ID code is composed of letters and numbers, where the letters identify the luminaire type and the numbers identify the electrical power).

3.9. Lighting design (Phase II, Step II.3)

The refurbishment design exercise involved a group of six roads (15% of the initial study sample and one for each group of sub-Sec. 3.2) representative of the present lighting environment in Pontedera (see Figure 17). All roads are not in compliance with CIE 115. In four roads (8, 11, 22 and 39) obsolete luminaires have been replaced with new ones while in two roads (4 and 31) it was necessary to change the layout of luminaires installation (i.e. distance), with consequent additional costs (see sub-Sec. 3.11). In Figure 18a the luminance mapping of *Tosco-Romagnola* carriageway calculated for the design situation has been reported, while, Figures 18b and 18c show a true-colours and a false-colours rendering of the horizontal illuminance mapping on the same road surface. In Figure 18 the increase of the luminance uniformity and the decrease of the illuminance levels, with respect to the present status, can be observed. The obtained values of luminance and illuminance are fully compliant with the requirements. The subdivision in the three-time bands shown in Figure 19 has been possible thanks to an observation of Pontedera traffic conditions at night-time.

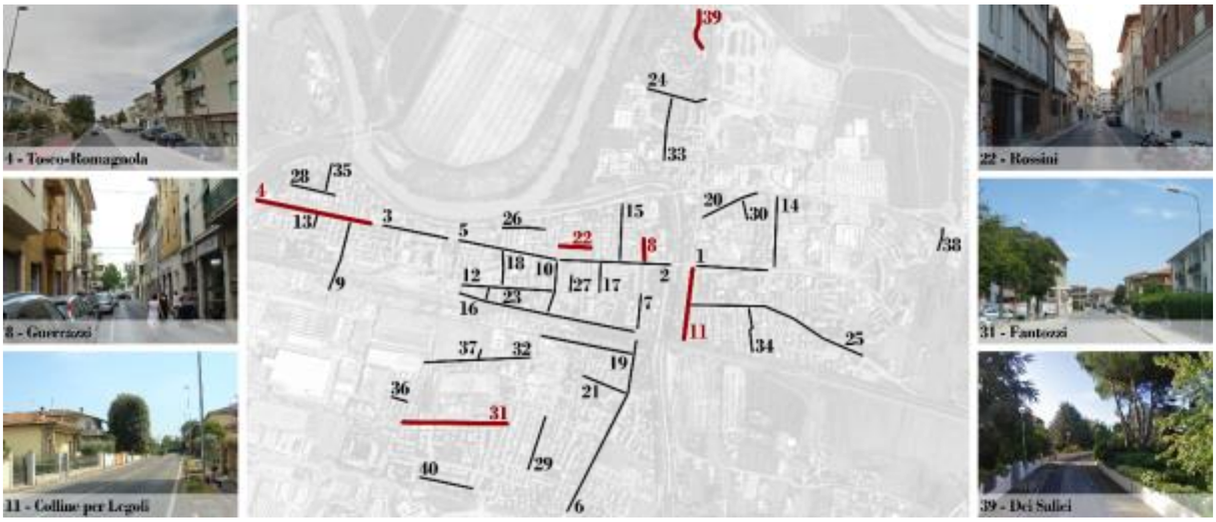


Figure 17. Location of the 6 roads involved in the refurbishment design: 4 *Tosco-Romagnola*, 8 *Guerrazzi*, 11 *Colline per Legoli*, 22 *Rossini*, 31 *Fantozzi* and 39 *Dei Salici*.

In order to re-select the new lighting classes for the three-time bands, the option of the traffic volume parameter has been decremented by a step (see Annex A for the different possible options). In time band III, the option low of the ambient luminance has been chosen rather than the moderate one. In Table 6, as example, the selection of the new lighting classes in night-time bands for *Tosco-*

Romagnola road has been summarized. In Figure 20 the multiplying factors of the luminous flux emitted by luminaires are summarized, showing how the devices can be dimmed at night in every road while continuing to guarantee the minimum safety requirements established by the corresponding time dependent lighting classes.

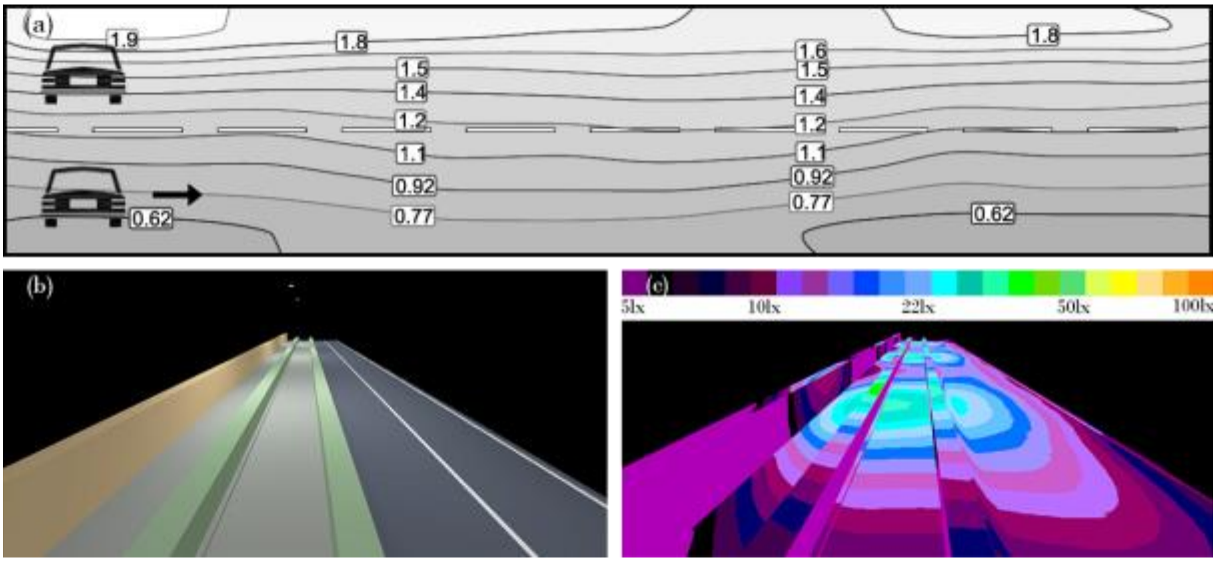


Figure 18. *Tosco-Romagnola* road software output at the design status: (a) luminance mapping (cd/m^2) for the carriageway; (b) and (c) true-colours and false-colours rendering of the horizontal illuminance mapping (lx).

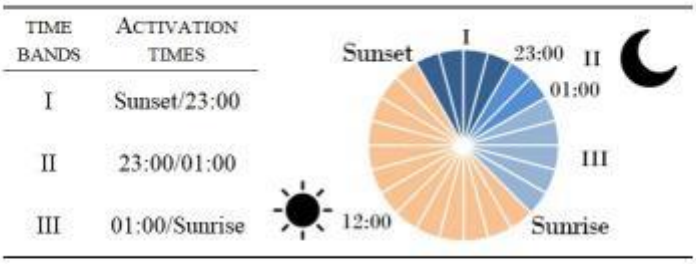


Figure 19. Scheme of the time bands adopted for the Pontedera street lighting refurbisment.

3.10. Check of the overall energy efficiency of new lighting systems (Phase II, Step II.4)

The design options for the new lighting systems have been evaluated through the following energy performance indicators: IPEA, IPEI, D_P, and D_E. Figure 21 shows a radar diagram reporting the four indicators calculated for the carriageways of the six roads where it is possible to compare in a quick way the present and the design values. The chosen design options respect the conditions of sub-Sec. 2.2.

For an overall evaluation of the energy efficiency improvement of the luminaires and of the lighting systems, the difference of areas of Figure 21 between the present and design status have been calculated. At the present status, the biggest area difference corresponds to *Dei Salici* road, the worst road of the sample group in terms of energy efficiency. The smallest area difference is for *Colline per Legoli* road, where luminaires with a fair IPEA class are installed. At the design status, the smallest areas are for *Tosco-Romagnola* and *Fantozzi* roads where luminaires arrangements are changed. In radar diagrams of Figure 21 the average percentage difference, between the areas at the present and at the design status, is about 80% while the minimum percentage of improvement in terms of energy efficiency is for *Colline per Legoli* road (about 60%).

Regarding D_P and D_E indicators, EN 13201-5 standard does not provide threshold values, they can be evaluated with their respective values at the present status (comparison in Figure 21). Both for D_E and D_P indicator the average improvements are about 60%, so on average, their values decrease more than half and anyway the individual improvements are never lower than 33% for D_E and 46% for D_P indicator. Dealing with the IPEI indicator, all the carriageways meet the minimum acceptable energy class and 50% of them are in IPEI class A or higher (see Table 7). Finally, the avoided equivalent CO_2 emissions in the atmosphere have been evaluated. On a total of only six roads, every year, 8.6 tons of CO_2 can be avoided corresponding to 4.41 tons/km.

TOSCO-ROMAGNOLA ROAD		Time bands		
Road area	Parameters	I	II	III
Carriageway	Speed	0.0	0.0	0.0
	Traffic volume	1.0	0.5	0.0
	Traffic composition	0.0	0.0	0.0
	Separation of carriageways	1.0	1.0	1.0
	Intersection density	0.0	0.0	0.0
	Parked vehicles	0.5	0.5	0.5
	Ambient luminance	0.0	0.0	-1.0
	Visual guidance / traffic control	0.0	0.0	0.0
	$6-\sum V_w$	3.0	4.0	5.0
	Lighting class	M3	M4	M5
Bicycle lane	Speed	1.0	1.0	1.0
	Traffic volume	1.0	0.5	0.0
	Traffic composition	0.0	0.0	0.0
	Parked vehicles	0.5	0.5	0.5
	Ambient luminance	0.0	0.0	-1.0
	Facial recognition	no	no	no
	$6-\sum V_w$	3.0	4.0	5.0
	Lighting class	P3	P4	P5
Sidewalk	Speed	0.0	0.0	0.0
	Traffic volume	1.0	0.5	0.0
	Traffic composition	0.0	0.0	0.0
	Parked vehicles	0.5	0.5	0.5
	Ambient luminance	0.0	0.0	-1.0
	Facial recognition	yes	yes	yes
	$6-\sum V_w$	4.0	5.0	7.0
	Lighting class	P4	P5	P6

Table 6. Selection of lighting classes depending on the night-time bands for *Tosco-Romagnola* road.

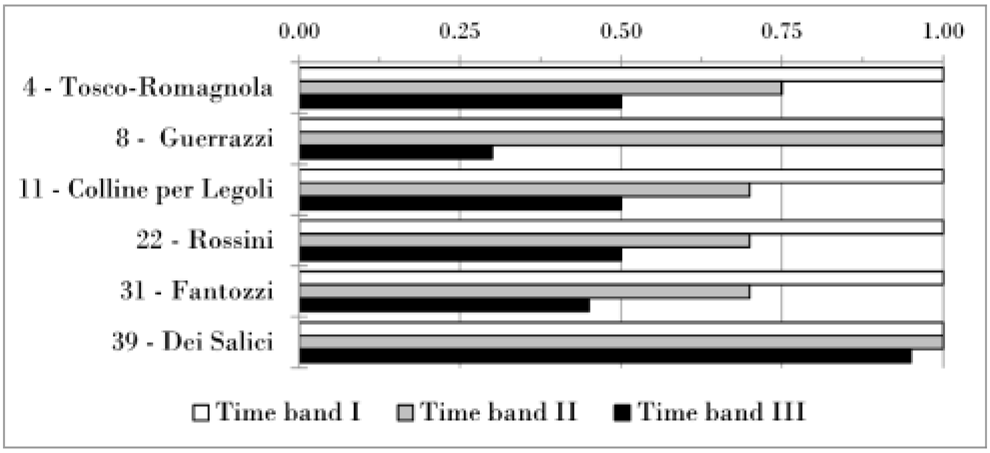


Figure 20. Multiplying factors of the luminous flux emitted (ϕ_{lum}) showing how the luminaires can be dimmed in every road depending on the time bands.

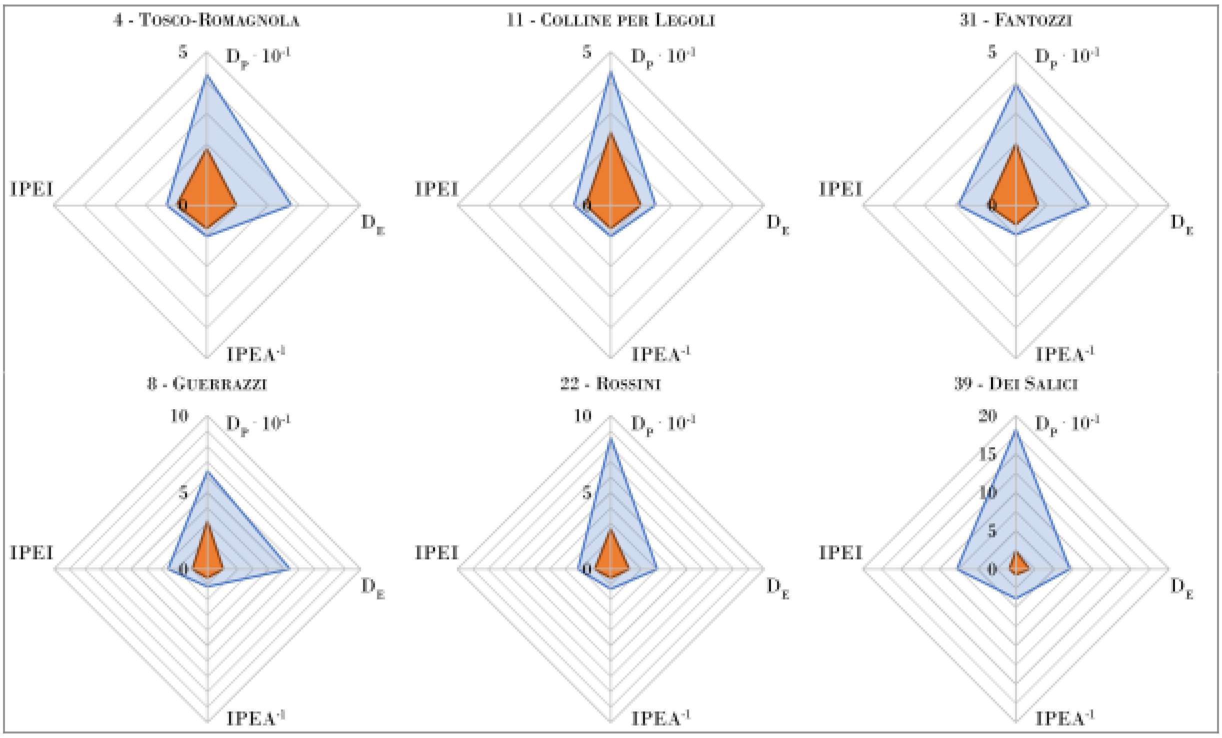


Figure 21. Energy efficiency comparison between present (blue line) and design status (orange line) for the carriageways.

	Roads	Present status			Design status			percentage reduction	
		IPEI value	IPEI class	CO_2 [tons/year]	IPEI value	IPEI class	CO_2 [tons/year]	IPEI	CO_2
4	Tosco-Romagnola	1.31	C	4.6	0.98	B	1.8	25	60
8	Guerrazzi	2.56	E	0.9	0.97	B	0.2	62	81
11	Colline per Legoli	1.20	C	1.4	0.81	A^+	0.9	33	33
22	Rossini	2.14	E	1.9	1.04	B	0.8	51	60
31	Fantozzi	1.87	E	3.3	0.91	A	1.9	52	41
39	Dei Salici	7.69	G	2.9	0.86	A	0.7	89	75

Table 7. Values of the IPEI indicator for the lighting systems on the carriageways and CO_2 emissions at present and design status.

3.11. Assessment of economic value of the investments (Phase III, Step III.1)

The economic values of the investments necessary for the roads refurbishment are shown in Table 8. Roads that require a major investment are *Tosco-Romagnola* and *Fantozzi*, since the entire lighting system needs to be restored. For these roads, it is not possible to meet the safety requirements while maintaining the old installation geometry (see also sub-Sec. 3.9). Between the two roads, *Fantozzi* road requires a greater investment due to the use of a two-staggered installation geometry for compliance with minimum performance requirements.

The costs of the new luminaires have been deduced from the price list of the manufacturer. The other costs have been taken from the official price list in force by law published by Tuscany region. The workmanship costs have been compared with the Pontedera public lighting specifications in order to have similar values.

3.12. *Calculation of economic savings (Phase III, Step III.2)*

Annual money savings, due to reduced electrical energy consumptions and to lower maintenance costs, have been calculated with Eq. (1) shown in Annex D. Assumptions have been detailed in Table 9. The cost of electricity has been assumed to be equal to C_{kWh}=0.167 €/*kWh*. The cost of the kilowatt per hour, valid for the quarter of January, February and March 2017, has been deduced from the Italian National Electric Service site [50]. Table 10 summarizes the global annual economic savings (*R*) obtained by the refurbishment design. Overall, it is possible to save up to 70% of money while, looking at each road, the minimum achievable savings are never less than 40%. This shows that the refurbishment design, in addition to increasing road users safety, also saves a non-negligible portion of public resources.

Roads		Specific cost for road refurbishment [€/m]	Investment for road [€]
4	Tosco-Romagnola	66	30 625
8	Guerrazzi	51	5 583
11	Colline per Legoli	16	5 436
22	Rossini	36	12 292
31	Fantozzi	104	45 932
39	Dei Salici	47	11 356

Table 8. Total and specific investment for roads refurbishment.

Road	Status	Luminaire ID	n_L	P_r [W]	t (multiplying factor) t_I [h/year]	t_{II} [h/year]	t_{III} [h/year]	d [$h \cdot 10^3$]	c_L [€/lamp]	c_M [€/lamp]
4	P	F-2	13	2 158	1 820 (1.00)	2 180 (0.80)	-	12	45.1	27.3
		B	21	1 758	1 820 (1.00)	2 180 (0.80)	-	12	30.8	11.7
	D	Ph138	14	1 932	1 455 (1.00)	725 (0.75)	1 820 (0.50)	100	174.0	27.3
8	P	A-1	6	683	4 000 (1.00)	-	-	12	41.2	27.3
	D	Ph32	6	192	1 455 (1.00)	725 (1.00)	1 820 (0.30)	100	134.0	27.3
11	P	F-2	7	1 162	1 820 (1.00)	2 180 (0.80)	-	12	45.1	27.3
	D	Ph138	7	966	1 455 (1.00)	725 (0.70)	1 820 (0.50)	100	174.0	27.3
22	P	A-3	13	1 482	4 000 (1.00)	-	-	8	95.4	27.3
	D	Ph63	13	819	1 455 (1.00)	725 (0.70)	1 820 (0.50)	100	138.0	27.3
31	P	F-5	18	2 808	1 820 (1.00)	2 180 (0.80)	-	8	97.8	27.3
	D	Ph56	19	1 064	1 455 (1.00)	725 (0.70)	1 820 (0.45)	100	166.0	27.3
39	P	C	19	2 204	4 000 (1.00)	-	-	12	41.2	11.7
	D	Ph30	19	570	1 455 (1.00)	725 (1.00)	1 820 (0.95)	100	131.0	11.7

Table 9. Assumptions made for the economic analysis at present and design status. (Legend: P, Present status; D, Design status; n_L, Total number of installed luminaires in the road; P_r, Total installed power in a road; t, Total annual number of operating hours for each time band; d, Average lifetime of the lamp; c_L, Cost of the lamp; c_M, Maintenance cost necessary to replace the lamp).

Roads		A_p [€/year]	A_d [€/year]	B [€/year]	C [€/year]	R [€/year]
4	Tosco-Romagnola	2 347	939	545	82	1 871
8	Guerrazzi	456	87	137	26	479
11	Colline per Legoli	692	463	150	40	338
22	Rossini	990	393	798	62	1 333
31	Fantozzi	1 671	494	1 003	102	2 078
39	Dei Salici	1 472	372	335	118	1 318

Table 10. Global economic savings (R, €/year) at the design status. (Legend: A_p, Cost of present electricity bill; A_d, Cost of electricity bill after the refurbishment design; B, Annual maintenance costs at the present status; C, Annual maintenance costs at the design status).

	Roads	Capital investment [€]	R [€/year]	SPT [years]
4	Tosco-Romagnola	30 625	1 871	16
8	Guerrazzi	5 583	479	12
11	Colline per Legoli	5 436	338	16
22	Rossini	12 292	1 333	9
31	Fantozzi	45 932	2 078	22
39	Dei Salici	11 356	1 318	9

Table 11. Payback period of the investments (SPT).

Total investments SPT [years]						
		kWh cost				
		–20%	–10%	0	10%	20%
	–20%	16	15	**14**	13	**12**
LED	–10%	17	15	**14**	13	13
Luminaires	0	**17**	**16**	**15**	**14**	**13**
Cost	10%	18	17	**16**	15	14
	20%	**19**	17	**16**	15	14

Table 12. Sensitivity analysis on simple payback time of the total investments.

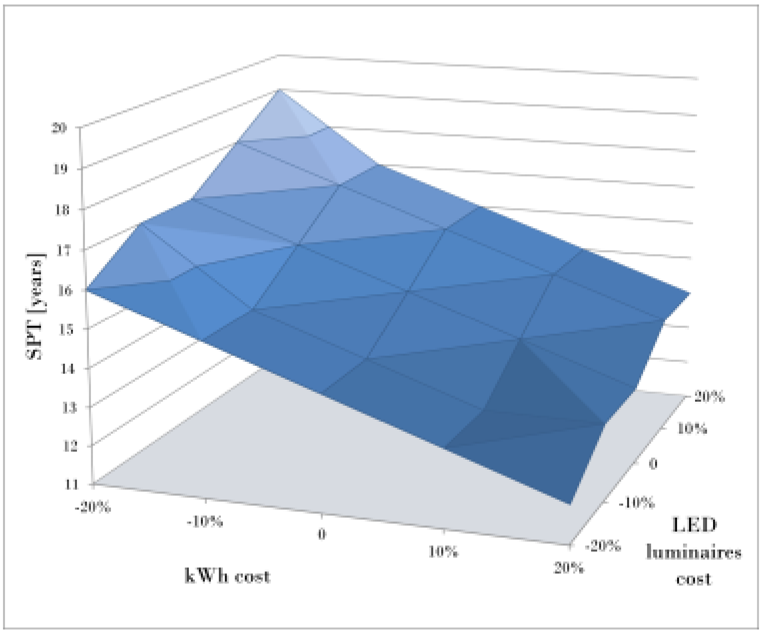


Figure 22. SPT sensitivity depending on variations of kWh cost and LED luminaires cost.

3.13. Calculation of payback time of investments (Phase III, Step III.3)

In order to provide useful information for evaluating the economic feasibility of the lighting design for every road, in Table 11 the SPTs have been calculated with Eq. (2) shown in Annex D. From Table 11, it is possible to note that *Rossini* and *Dei Salici* roads show very interesting SPT values of 9 years. *Guerrazzi*, *Tosco-Romagnola* and *Colline per Legoli* roads have an acceptable SPT (16-year). The higher SPT is obtained for *Fantozzi* road, where is needed a re-design of luminaires installation geometry. The refurbishment of *Fantozzi* road is not economically sustainable because SPTs higher than 20 years are not compatible with the financial planning of a municipal administration.

It is possible to evaluate the SPT of all the roads, as the case study of the refurbishment of a group of roads. Considering the total of investments, we have a 15-year return time, which is quite acceptable.

Evaluating the payback period considering only roads where luminaires are replaced, we find a SPT significantly lower and equal to 10 years. This is a result in line with similar cited studies [10, 18], where obsolete luminaires are replaced without varying the installation geometry (in general, this choice could not guarantee the respect of all the minimum safety requirements).

3.14. Analysis of payback time of investments (Phase III, Step III.4)

Considering the total investments of all the six roads, a payback sensitivity analysis has been made and the SPT has been recalculated , taking into consideration reasonable variations of electricity and LED luminaires costs. For both the variables, the variation range has been set to –20% and +20% from the central value, as stated in sub-Sec. 2.3. From Table 12, regarding the total investments and the variations of the costs, the SPTs are variable between 12 and 19 years. The most favourable situation is obtained for an increase of 20% of electricity cost and a decrease of 20% of LEDs cost, vice versa for the opposite case. For null changes in LED luminaires costs, there is a variation of SPT of ±2 years; for null changes of kWh costs, there is a variation of only ±1 year (see also Figure 22). Looking at the rising of Italian electricity cost trends and at the decreasing of LED luminaires cost, the more significant results of Table 12 are highlighted in grey. For these conditions, the range of SPT is reduced considerably and varies only between 12 and 15 years, with an estimated average value of 13-year. These considerations make the investment for public street lighting refurbishment even more convenient.

4. CONCLUSIONS

Street lighting is very important for road user safety and city's night landscape, participates with high shares in municipalities economic budgets and often lighting systems in many Italian towns have problems of energy waste and light pollution. Hence the need to define a methodology for a lighting, energy and economic analysis of refurbishment of street lighting.

The methodology proposed in this paper is a step by step process suitable for street lighting refurbishment designs of towns of different sizes. It can be used by lighting designers as a valuable tool to propose street lighting designs and from municipalities to compare different lighting refurbishment design options.

From the analysis of the present status of Pontedera public street lighting, clearly emerged the typical issues of Italian towns involving the safety of road users and the low energy efficiency of the lighting systems. In fact, the 70% of Pontedera's roads do not guarantee the minimum safety lighting requirements while the 90% of the lighting systems appear energetically inefficient. Hence the need to restore safety conditions and compliance with current regulations. Of course, the opportunity can be exploited to improve the energy and environmental sustainability of the lighting systems and the benefits that would come from improving the quality of light and the lower emissions in the atmosphere cannot be neglected. With the adopted methodology, it has been shown that on average is possible to save the emission of 4.41 tons/km of CO_2 in the Earth's atmosphere.

After the refurbishment design, it has been pointed out that money savings, due to the reduced electricity bill and to maintenance costs, could be achieved. For every road, annual costs can be reduced by at least one third (33%) with respect to the present costs and consequently a release of a portion of public economic resources can be free. The economic analysis showed that the necessary interventions have a payback on investments more than acceptable for a municipality (on average 13-years). The payback values showed a greater sensitivity to variations of electricity cost while LED luminaires cost variations have a reduced impact.

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ANNEX A – LIGHTING CLASSES FOR ROAD AREAS AND LIGHTING CLASSES SELECTION

The minimum lighting requirements for road areas are related to the visual tasks of users. In the CIE 115 recommendation [5], the road areas are divided (in relation to the expected traffic type) in: Motorized (M), intended for drivers of motorized vehicles on traffic routes; Conflict (C), intended for use on conflict areas on traffic routes where the traffic composition is mainly motorized; Pedestrian and low speed (P), intended predominantly for pedestrians and cyclists for use on footways and cycle ways, and drivers of motorized vehicles at low speed on residential road.

For the motorized areas (M) are defined six lighting classes (from M1 to M6) and for each one the limit values of the average road surface luminance (L_{av}), the overall uniformity of the luminance (U_o), the longitudinal uniformity of the luminance (U_l) and the threshold increment (TI) are provided. Note that U_o is defined as ratio of the lowest to the average road surface luminance found in the whole carriageway, while U_l as ratio of the lowest to the highest road surface luminance found in the centre line along each driving lane of the carriageway. For the conflict areas (C) are defined six lighting classes (from C0 to C5) and for each class the limit values of the average value of the horizontal illuminance ($E_{h,av}$), the overall uniformity of the horizontal illuminance (U_o) and the threshold increment (TI) are provided. Note that U_o is defined as ratio of the lowest to the average horizontal illuminance. For the pedestrian and low speed areas (P) are defined six lighting classes (from P1 to P6) and for each class the limit values of the average horizontal illuminance ($E_{h,av}$), the minimum horizontal illuminance ($E_{h,min}$), the minimum vertical plane illuminance ($E_{v,min}$) and the minimum semi- cylindrical illuminance ($E_{sc,min}$) are provided.

For the selection of the M lighting class, the appropriate weighting values ($V_{w,M}$) for the different parameters given in Table A.1 have to be applied. For C lighting class selection, the appropriate weighting values ($V_{w,C}$) for the different parameters given in Table A.1 have to be applied. Finally, for P lighting class selection, the appropriate weighting values ($V_{w,P}$) for the different parameters given in Table A.1 have to be applied. After the weighting choice, their values must be respectively added to find the sum of the weighting values $\sum V_w$ (rounded to the next greater whole number). The number of the lighting class M (or C or P) is then calculated as:

$$\text{M (or C or P)} = 6 - \sum V_{w,i} \qquad \text{with} \qquad i = M \text{ (or C or P)}$$

PARAMETER	OPTIONS	WEIGHTING VALUE, $V_{w,M}$
Speed	Very high	1.0
	High	0.5
	Moderate	0.0
Traffic volume	Very high	1.0
	High	0.5
	Moderate	0.0
	Low	-0.5
	Very low	-1.0
Traffic composition	Mixed with high percentage of non-motorized	2.0
	Mixed	1.0
	Motorized only	0.0
Separation of carriageways	No	1.0
	Yes	0.0
Intersection density	High	1.0
	Moderate	0.0
Parked vehicles	Present	0.5
	Not present	0.0
Ambient luminance	High	1.0
	Moderate	0.0
	Low	-1.0
Visual guidance/ traffic control	Poor	0.5
	Moderate or good	0.0
		$\sum V_{w,M}$

PARAMETER	OPTIONS	WEIGHTING VALUE, $V_{w,C}$
Speed	Very high	3.0
	High	2.0
	Moderate	1.0
	Low	0.0
Traffic volume	Very high	1.0
	High	0.5
	Moderate	0.0
	Low	-0.5
	Very low	-1.0
Traffic composition	Mixed with high percentage of non-motorized	2.0
	Mixed	1.0
	Motorized only	0.0
Separation of carriageways	No	1.0
	Yes	0.0
Ambient luminance	High	1.0
	Moderate	0.0
	Low	-1.0
Visual guidance/ traffic control	Poor	0.5
	Moderate or good	0.0
		$\sum V_{w,C}$

PARAMETER	OPTIONS	WEIGHTING VALUE, $V_{w,P}$
Speed	Low	1.0
	Very low (walking speed)	0.0
Traffic volume	Very high	1.0
	High	0.5
	Moderate	0.0
	Low	-0.5
	Very low	-1.0
Traffic composition	Pedestrians, cyclists and motorized traffic	2.0
	Pedestrians and motorized traffic	1.0
	Pedestrians and cyclists only	1.0
	Pedestrians only	0.0
	Cyclists only	0.0
Parked vehicles	Present	0.5
	Not present	0.0
Ambient luminance	High	1.0
	Moderate	0.0
	Low	-1.0
Facial recognition	Necessary: additional requirements	
	Not necessary: no additional requirements	
		$\sum V_{w,P}$

Table A.1. Parameters for the selection of lighting classes: M lighting classes (left); C lighting classes (center); P lighting classes (right).

ANNEX B – SPACE SYNTAX ANALYSIS

For assessing traffic conditions, instead of a traffic observation campaign, a space syntax analysis has been adopted. The employed methodology can be summed up in the form of a syllogism (see Table B.1).

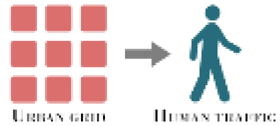
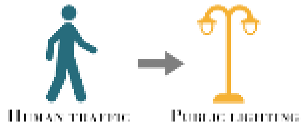
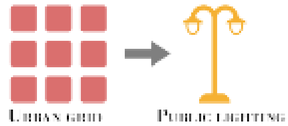
1.	Human movements in a city can be predicted through a space syntax analysis;	
2.	An efficient public street lighting must adapt to the actual traffic levels foreseeable in a city;	
3.	Public lighting design can take advantage of the space syntax analysis results to adapt to the real conditions of public spaces use.	

Table B.1. Concept of the adopted methodology for assessing traffic conditions.

Hillier and Hanson published a syntactic theory for the pattern of space and interaction in the built environment in *"The Social Logic of Space"* in 1984 [51]. In the book they argued that cities have complex spatial properties which affect social rules and how people relate to one another. They discussed that space is not as the background to human activity, but as an intrinsic aspect of every human movement. Furthermore, space seemed to identify structures which linked the social and the spatial sphere [52]. Space syntax theory attributes to the urban street grid the role of main generator of the phenomena that occur on it. So urban grid conformation determines formation and intensity of traffic inside it and determines the conditions for human activities localization [53]. In other words, the configuration of the urban street network is in itself a major determinant of movement flows [38].
Among the various space syntax techniques available, the axial analysis has been adopted. Axial analysis assumes that urban space is articulated into a plot of line. Each straight line corresponds to a human line of sight: it is assumed that an observer perceives the space of the city by straight lines corresponding to his visual perspectives and his movements in the city are guided by them [54].
Axial analysis has been operationalised decomposing the urban grid in the convex map. Urban grid is the set of public spaces freely accessible by citizens while convex map is the set of urban places of greater area (or 'perceptual unit') and taken in their smaller number. Afterwards, it is possible to define the axial map. Axial map is the set of lines (axial lines) connecting each other the convex spaces. Axial lines are as long as possible and in their smaller number. Axial lines do not identify themselves with geometric but topological measurements, as they represent the lines of view of citizens [41]. With the axial map, it is possible to calculate different measurements (syntactic measures) that allow to give a quantitative value to the representation.
Axial analysis can be automated with the help of software. In this work UCL Depthmap X software, developed by the Centre for the Built Environment of the UCL Bartlett School of Graduate Studies, has been used [55]. Software produces outputs such as colour charts and numeric tables which compare the various syntactic measures produced. Among the various syntactic measures, the global integration index ($I_{[r=n]}$) has been used. $I_{[r=n]}$ describes the mean depth of a line respect all other lines of the axial map. Mean depth is defined as the topological distance separating a pair of lines and it is measured as the number of lines interposed along the shortest path between the two lines.

$I_{[r=n]}$ is defined by the following equation:

$$I_{[r=n]} = \frac{k-1}{D_t}$$

where D_t is the total depth of a line, equal to the sum of the mean depths respect all the other lines and k is the total number of lines of the axial map. $I_{[r=n]}$ quantifies how close a given street is from all other streets. The greater the integration value of a line in a system is, the more accessible and integrated is in the system, vice versa the line is more isolated and segregated [56, 57].

In Figure B.1 is presented the axial analysis of Pontedera. In particular, the global integration index is shown with a chromatic scale. The colour scale runs from a blue tinged magenta for the very lowest value, to blue (through cyan), to green (through yellow) to red, and up to a red tinged magenta, for the very highest value [58]. For assessing traffic conditions, and so for the right choice of the option for traffic volume parameter of Table A.1, Table B.2 has been adopted. The use of space syntax analyses as a tool for assessing traffic flows in a city has been analysed and confirmed in a lot of case studies [39, 41, 52, 54, 56, 59, 60].

Figure B.1. Distribution of the global integration index ($I_{[r=n]}$) values for the axial map of Pontedera.

TRAFFIC VOLUME	$I_{[r=n]}$		
Very high	2.48 – 2.10		+ integrated roads
High	2.10 – 1.71		
Moderate	1.71 – 1.33		URBAN CENTRALITY
Low	1.33 – 0.95		
Very low	0.95 – 0.56		- segregated roads

Table B.2. Breakdown of global integration index ($I_{[r=n]}$) values in five ranges for traffic volume parameter evaluation.

ANNEX C – ENERGY PERFORMANCE INDICATORS FOR ROAD LIGHTING SYSTEMS

Table C.1 shows the equations for the calculation of the energy performance indicators introduced by [33] and [37]. Table C.2 shows the energy classes for the IPEA and IPEI performance indicators [37].

STANDARD REFERENCE	ENERGY PERFORMANCE INDICATOR	UNITS	EQUATIONS	SYMBOLS	
[33]	Power Density (D_P)	$\left[\frac{W}{lx \cdot m^2}\right]$	$D_P = \frac{P}{\sum_{i=1}^{N}(E_i\ A_i)}$	$P\ [W]$	Power absorbed by the luminaire resulting from the sum of the powers absorbed by both the lamp and the electrical supply components;
				$E\ [lx]$	Maintained average horizontal illuminance;
				$A\ [m^2]$	Surface area to be lit;
				N	Total number of sub-areas to be lit.
[33]	Annual Energy Consumption (D_E)	$\left[\frac{Wh}{m^2}\right]$	$D_E = \sum_{i=1}^{M}(P_i t_i) A$	$P\ [W]$	Actual power absorbed by the luminaire;
				$t\ [h]$	Duration of the operating time;
				$A\ [m^2]$	Surface area to be lit;
				M	Numbers of periods with different operational power P_i (M shall also consider the period over which the quiescent power is consumed, this period would generally be the time when the lighting is not operative).
[37]	Luminaire Energy Efficiency (IPEA)	-	$\text{IPEA} = \frac{\eta_a}{\eta_r}$ $\eta_a = \eta_l \cdot \eta_s \cdot D_{lor}$	$\eta_a\ [lm/W]$	Luminous efficacy;
				$\eta_r\ [lm/W]$	Standard luminous efficacy value indicated in [30];
				$\eta_l\ [lm/W]$	Luminous efficacy of the lamp;
				$\eta_s\ [lm/W]$	Power supply efficacy (ratio between the lamp nominal power and the input power supply having possible auxiliary loads);
				D_{lor}	Ratio between the luminous flux emitted downwards by the luminaire and the total luminous flux emitted by the lamps.
[37]	Illuminance based Lighting systems Energy Efficiency (IPEI_E)	-	$\text{IPEI}_E = k_E \frac{SE}{SE_R}$ $k_E = K_1\left(\frac{E_{h,av}}{E_{h,av,R}} + K_2\right)$	SE	SLEEC relative to illuminance;
				SE_R	Standard SLEEC relative to illuminance value indicated in [30];
				$E_{h,av}\ [lx]$	Average horizontal illuminance on the standard area;
				$E_{h,av,R}\ [lx]$	Limit value of illuminance required by standards for the corresponding lighting class;
				K_1	Constant value equal to 0.476;
				K_2	Constant value equal to 0.524.
[37]	Luminance based Lighting systems Energy Efficiency (IPEI_L)	-	$\text{IPEI}_L = k_L \frac{SL}{SL_R}$ $k_L = K_1\left(\frac{L_{av}}{L_{av,R}} + K_2\right)$	SL	SLEEC relative to luminance;
				SE_R	Standard SLEEC relative to luminance value indicated in [30];
				$L_{av}\ [cd/m^2]$	Average luminance on the standard area;
				$L_{av,R}\ [cd/m^2]$	Limit value of luminance required by standards for the corresponding lighting class;
				K_1	Constant value equal to 0.476;
				K_2	Constant value equal to 0.524.

Table C.1. Summary of the main energy performance indicators for road lighting systems.

IPEA CLASS	IPEA VALUE
A^{++}	1.15 < IPEA
A^{+}	1.10 < IPEA ≤ 1.15
A	1.05 < IPEA ≤ 1.10
B	1.00 < IPEA ≤ 1.05
C	0.93 < IPEA ≤ 1.00
D	0.84 < IPEA ≤ 0.93
E	0.75 < IPEA ≤ 0.84
F	0.65 < IPEA ≤ 0.75
G	IPEA ≤ 0.65

IPEI CLASS	IPEI VALUE
A^{++}	IPEA < 0.75
A^{+}	0.75 ≤ IPEI ≤ 0.82
A	0.82 ≤ IPEI ≤ 0.91
B	0.91 ≤ IPEI ≤ 1.09
C	1.09 ≤ IPEI ≤ 1.35
D	1.35 ≤ IPEI ≤ 1.79
E	1.79 ≤ IPEI ≤ 2.63
F	2.63 ≤ IPEI ≤ 3.10
G	3.10 ≤ IPEI

Table C.2. Energy classes in function of IPEA and IPEI values (in grey the minimum class required by [37]).

ANNEX D – ECONOMIC FEASIBILITY OF INTERVENTIONS (SIMPLE PAYBACK TIME)

After a refurbishment design of a street lighting, the global annual savings achievable can be calculated as the difference between the costs at present and at the design status. Annual money savings are due to the reduced electrical energy consumptions and to the lower maintenance costs of the new lighting systems. The global economic savings (R, €/year) can be calculated according to the following equation:

$$R = A + B - C = \left(A_p + B\right) - \left(A_d + C\right) \tag{1}$$

with:

$$A = A_p - A_d = \left(P_p\, t_p\right) \cdot C_{kWh} - \left(P_d\, t_d\right) \cdot C_{kWh}$$
$$B = \sum_{i=1}^{k} \left(t_{p_i} / d_{p_i}\right) \cdot \left(c_{L_i} + c_{M_i}\right) \cdot n_{pL_i}$$
$$C = \sum_{i=1}^{k} \left(t_{d_i} / d_{d_i}\right) \cdot \left(c_{L_i} + c_{M_i}\right) \cdot n_{dL_i}$$

where: A (€/year) economic savings due to the reduced installed power; B (€/year) annual maintenance costs at the present status; C (€/year) annual maintenance costs at the design status; A_p (€/year) cost of present electricity bill; A_d (€/year) cost of electricity bill after the refurbishment design; P_p (W) total installed power on a road at the present status; P_d (W) total installed power on a road at the design status; t_p (h/year) total annual number of operating hours of the luminaires at the present status; t_d (h/year) total annual number of operating hours of the luminaires at the design status; C_{kWh} (€/kWh) electricity cost; t_{pi} (h/year) total annual number of operating hours of the *i*-th luminaire at the present status; t_{di} (h/year) total annual number of operating hours of the *i*-th luminaire at the design status; d_{pi} (h) average lifetime of the lamp of the *i*-th luminaire at the present state; d_{di} (h) average lifetime of the lamp of the *i*-th luminaire at the design status; c_{Li} (€) cost of the *i*-th lamp; c_{Mi} (€/lamp) maintenance cost (necessary to replace the *i*-th lamp); n_{pLi} total number of installed lamps of the *i*-th luminaire at the present status; n_{dLi} total number of installed lamps of the *i*-th luminaire at the design status.

To evaluate the economic feasibility of a refurbishment design, the Simple Payback Time (SPT, year) can be evaluated. The SPT is a parameter frequently adopted because of its simplicity of use and computation. It does not claim to replace an in-depth economic analysis but is still able to provide an immediate evaluation of the convenience of an investment. The SPT indicates the number of years necessary to make the annually earned savings match the costs incurred to get them. SPT can be calculated according to the following equation:

$$SPT = Capital\ investment / R \tag{2}$$

The capital investment necessary for the refurbishment design can be estimated through a detailed list of materials, workmanship and present market costs.