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Space Syntax Analysis Applied to Urban Street Lighting: Relations between Spatial Properties and Lighting Levels

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Abstract: According to the international technical standards, higher lighting levels (luminance and illuminance levels) are expected in trafficked and central roads (where restrictive minimum lighting requirements are necessary) and lower lighting levels are expected in peripheral and less trafficked roads. Starting from this assumption, in this paper, the authors analyse the correlations between spatial properties (expressed by spatial indicators, for example, the integration index and the choice index) and lighting levels (expressed by lighting parameters, for example luminance and illuminance) upon roads of an urban context. The analysis has been applied to the case study of the medium sized town of Pontedera (central Italy). From the obtained results, it has been possible to observe how the correlations between integration index and luminance and illuminance values are significant in the case of roads equipped with lighting systems able to satisfy the lighting requirements established by the regulations. The presence of the discussed correlations lays the foundation for a change in the lighting design approach on urban scale, being able to set lighting requirements on the basis of space syntax results without the use of traditional methods of road classifications involving traffic volume estimations.

Keywords: urban street lighting; space syntax analysis; lighting refurbishment design; lighting measurements; lighting simulations

1. Introduction

Night visibility is a significant issue for people's movements and activities in a town. Night visibility is mainly due to urban street lighting, which has the increment of people's hours of activity as the primary goal. This goal can be achieved by improving the attractiveness of the town and helping citizen's night-orientation, so that people can continue their activities after sunset [1,2]. Urban street lighting increases the people's perception of safety, improving their visual comfort [3–5]. Furthermore, a well-designed street lighting system improves traffic management and road user safety, decreasing the risk of road accidents [6,7]. On the other hand, street lighting service has relevant costs and a great impact on energy consumptions in most municipalities. For example, in the Netherlands, the energy used by municipalities for public lighting accounts for 60% of their electricity consumption, while in some Spanish municipalities street lighting service may account for up to 80% of electricity consumption [8,9]. Nineteen percent of the world's electricity production is consumed for illumination purposes and 3% of global worldwide electricity is consumed for public lighting [10]. For this reason, it is important to assess lighting levels based on the actual use of roads to avoid oversized lighting systems and light pollution phenomena. A reduction of light pollution phenomena and an improvement of the sustainability of the lighting systems (e.g., contributing to a reduction of the greenhouse effect) is possible with well-designed systems. A well-designed lighting system is planned on the basis of the minimum lighting requirements. Such requirements for roads, established by in force regulations or recommended by specific guidelines, are given as a function of lighting classes, whose selection procedure is mainly based on the intensity of traffic volumes [11]. Therefore, the knowledge of traffic volumes within an urban context is important for the respect of the minimum lighting requirements, to avoid oversized lighting systems and electricity waste.

In order to analyse and predict the intensity of traffic volumes in an urban context, there are many techniques. Among these, the space syntax is very effective and accepted by the majority of urban planning and the scientific society [12]. Space syntax, through appropriate spatial indicators, is able to express the intensity and distribution of the traffic volumes in roads of a town. Therefore, it can be used as the basis for lighting planning strategies or for refurbishment designs of roads and groups of roads. Nowadays, in the scientific literature space syntax has already been applied to carry out urban studies and to projects focused on street lighting. For example, in 2017, Çamur et al. [13] used space syntax to evaluate public areas from the point of view of pedestrian safety, while Raval et al. [14] adopted space syntax as the basis for a methodology to estimate roads capacity in urban areas. In a more recent study, Kazemidemneh et al. [15] made a comparison between measured illuminance values and space syntax results for the city of Tehran to establish if illuminance levels were weighted upon traffic levels. In the case that the illuminance levels were too high, they proposed a design phase to reduce energy consumption. The study of Choi et al. [16], although published in 2006, is interesting because it reveals relationships between lighting parameters and spatial properties for some pedestrian roads of the city of Seoul in South Korea. Relations have been analysed for the present arrangement of the roads quite far from design requirements. The analysis shows very low values of correlation between lighting parameters and spatial properties. Nowadays, in the scientific literature analyses aimed at ascertaining and quantifying relationships between spatial properties and lighting levels in urban contexts are lacking. From this point of view, could be interesting carry out more in-depth analyses aimed at understanding how these relationships can vary following improving interventions on lighting performance and energy efficiency of the lighting systems.

Research Scope

The aim of this paper is to analyse potential relations between spatial properties of a town (expressed by spatial indicators) and lighting levels of a road in an urban context (expressed by luminance and illuminance values). Furthermore, it is essential to analyse how relations between spatial properties and lighting levels varies when the energy efficiency of the lighting systems increase or how relations varies, passing from roads that are in compliance with minimum lighting requirements, to roads that are not in compliance with such requirements.

A relation between the spatial properties and the lighting levels is expected for roads in compliance with minimum lighting requirements. They are established as a function of a lighting class selection procedure that is based on the intensity of traffic volumes. According to the standards, higher luminance and illuminance levels are expected in more trafficked and central roads, where there are more restrictive lighting requirements; lower values are expected in peripheral and less trafficked roads. On the other hand, a lack of correlation can certainly mean that the lighting levels do not correspond to the actual levels of use of the roads, but it could also mean that the roads do not meet the minimum lighting requirements or that the lighting systems are not energetically efficient. Having lighting levels corresponding to the actual use of roads, it is possible to optimize the energy consumption of the lighting systems, avoiding energy waste and oversized lighting systems.

In the paper, the analysis of the possible relations between spatial properties and lighting levels has been structured in three main phases, as shown in Figure 1. Specifically, the first phase (Section 2) represents the application of the space syntax analysis to an urban context, throughout a spatial indicators (i.e., integration and choice indices) assessment. The second phase (Section 3) represents the analysis of lighting levels for an urban context, throughout a lighting parameters (i.e., luminance and illuminance values) evaluation. The third phase (Section 4) represents the research of correlations between spatial indicators and lighting parameters. The analysis has been applied to the case study of a medium sized town in central Italy.

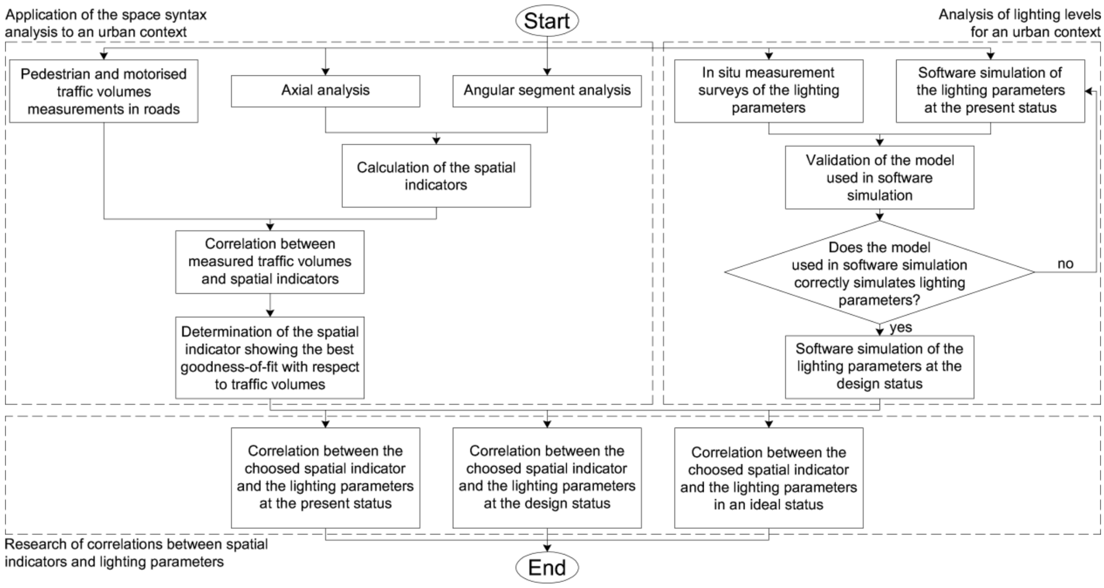


Figure 1. Flowchart showing the phases in which the research has been structured.

2. Application of the Space Syntax Analysis to an Urban Context

In this section, space syntax analysis has been applied to an urban context and precisely to a case study town. In Section 2.1, space syntax analysis theory is briefly illustrated. In Section 2.2, the used spatial indicators of space syntax are shown. In Section 2.3, a case study town is introduced and its space syntax analysis is presented. In order to evaluate the spatial indicators with the best goodness-of-fit with respect to the actual traffic volumes of the case study town, in Section 2.4, a pedestrian and motorised traffic observation campaign is shown and, in Section 2.5, correlations between traffic volumes and spatial indicators are presented. Throughout such analysis, the spatial indicator with the best goodness-of-fit with respect to observed traffic volumes is find out and it can be used for the subsequent assessment.

2.1. Space Syntax Analysis Theoretical Concepts

Space syntax is a set of techniques for the analysis of urban contexts affirming that the configuration of the urban street grid generates the traffic volumes inside an urban context [17]. Space syntax has been developed by Hillier and Hanson in the early 1970s and it is a method for sociospatial analysis [18,19]. Space syntax theory designates the urban street grid as the main generator of the traffic volumes inside itself [20]. According to space syntax theory, the traffic volumes inside an urban street grid are the sum of two components: natural and attracted movement [21]. The natural movement is the portion of the traffic volumes on each street that is determined by the configuration of the urban grid itself and not by the presence of human activities [22]. The attracted movement is determined by the presence of human activities [23]. The natural movement may not even be the dominant portion of the totality of the traffic volumes (in some cases it may be only a very small fraction), but nonetheless is recognised by the theory as the primary element generating the traffic volumes inside an urban context [24]. The human activities location inside an urban context is not a random one because each activity seeks to take advantage by streets where the benefits from the traffic volumes are the highest possible [25]. Therefore, a greater concentration of activities is expected in areas with higher traffic volumes (excluding monopolistic activities and those resulting from rigid placements) [26].

The most used space syntax techniques are the axial analysis, the angular segment analysis and the visibility graph analysis [27,28]. The visibility graph analysis is more suitable for building interiors because is adapted to spaces with defined areas and clear boundaries [29]. For this reason, the axial analysis and the angular segment analysis have been used in this research. The main difference between the standard urban study and space syntax approach is that the former focuses on metric distance as unit of measurement to calculate the shortest path between two points of an urban context; while the latter considers how streets visually connect with each other in a network to calculate the shortest path [30–32]. Axial analysis assumes that urban space is articulated into a plot of straight lines. Each line corresponds to a human's line of sight: by hypothesis an observer perceives the space of the city by straight lines corresponding to his perspectives and his movements in an urban context are guided by them [33]. The urban street grid can be defined as the set of all the public spaces (i.e., the spaces freely accessible to public transit). Practically, the urban grid is the set of all the streets and squares of the city [12]. Axial analysis and angular segment analysis can be performed subdividing the urban street grid in a set of convex polygons. The set of convex polygons is called convex map. The polygons are drawn in such a way to have the largest possible area and to subdivide the urban grid in the smaller possible number of polygons. Afterwards, it is possible to define the axial map that, based on the above convex map, is the minimal set of lines (axial lines) crossing and connecting every possible polygon. Axial lines are drawn as long as possible and in such a way to connect all the polygons with their fewest number. Axial lines represent the longest line of sight one has in an urban context or building and, in addition, the way humans move in lines through streets and roads or rooms and corridors [34]. The angular segment analysis is essentially an extension of the axial analysis. Indeed, in this latter case, the axial lines of the map are broken up into segments, from junction to junction. As regards the first method, each segment is weighted by the angle of its connections to other segments [35]. The choice to refer to the angle is supported by scientific evidence in the cognitive field [36].

Space syntax analysis is suitable both for pedestrian and vehicular traffic forecasting while recent studies are even aimed at extending its validity to generic variables such as land use, property or financial rents, noise pollution [37,38]. It must be underlined that more modelling problems appear with the vehicular traffic. For example, in an urban grid, roads in a traffic-restricted area must not be considered, and one-way roads represent a challenging modelling problem because at the present status the software does not consider the direction of travel of a road [39]. Another problem is the edge-effect because the analysis is not able to consider the traffic towards and from the city [40,41].

2.2. Spatial Indicators Assessment

By using the axial map both of the axial or of the angular segment analysis, it is possible to calculate different spatial indicators (syntactic measures) to give a quantitative value to the obtained representation. Among the various indicators, the integration (I) and the choice (Ch) indices have been used. The integration index (I) represents the accessibility of a given street within the urban grid, while the choice index (Ch) represents the extent to which a line or a segment functions as an intermediate location within the urban grid [42,43].

The I index describes the mean depth of a line respect all other lines of the axial map [33], it is defined as

$$I = (k - 1)/D_t$$

where k represents the total number of lines of the axial map and D_t represents the total depth of a line. The depth of a line is defined as the distance separating a pair of lines; it can be determined by the number of lines dividing the two lines along the shortest path between the two considered lines. The total depth of a line is the sum of the depths with respect to all the other lines (see example in Figure 2). The I index quantifies how close a given road (identified by a specific line or segment) is by all other roads. The greater the I value is, the more accessible and integrated the road results, and, vice versa, the lower the I value is, the more isolated and segregated the road results.

The *Ch* index counts the number of times a specific line or segment lies on the shortest path between all origin–destination pairs in the urban grid [44], if an axial map is made up of *k* lines, the *Ch* standardised value is calculated with the following equation.

$$Ch = \frac{N_l - (k-1)}{N_t - (k-1)}$$

where N_l represents the number of paths containing the line under examination and N_t represents the theoretical maximum number of possible paths. N_t can be calculated as

$$N_t = \binom{k}{2} = \frac{k!}{(k-2)! \cdot 2!}$$

The *Ch* index represents the frequency with which a line or a segment falls within the shortest paths that connect all lines to all the others in the system, excluding those to and from the considered line (see example in Figure 2). The *Ch* index gives a measure of the complexity of the road connections within the urban grid. When many of the shortest paths that connect all the spaces to all the others pass through the considered space there is a high value of choice. As for the *I* index, the *Ch* index depends on the number of lines in which the system is composed. N_l and N_t are both calculated not considering the paths starting or finishing with the considered line. The minimum value of the *Ch* index corresponds to the lines or segments that are only on the paths that affect them as terminal lines; while the maximum value corresponds to the case of the lines that are on all the paths that reciprocally connect each pair of lines or segments.

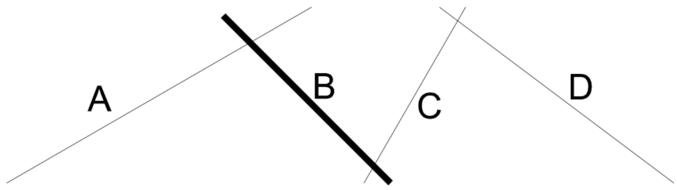


Figure 2. Space syntax indices calculation for the line B (marked line) in an example with 4 lines (streets). The depth between the lines B and A is 1 (because an observer performs only one change of perspective to go from B to A), between lines B and C is 1 and between lines B and D is 2. The total depth for the line B is $D_t = 1 + 1 + 2 = 4$ and the total number of lines of the system is $k = 4$, so the integration index value is $I = 3/4$. All the possible paths between the four lines are A–B, A–B–C, A–B–C–D, B–C, B–C–D and C–D ($N_t = 6$). The paths containing the line B are 5 ($N_l = 5$). The choice index is $Ch = (5 - 3)/(6 - 3) = 2/3$.

2.3. Space Syntax Analysis of Pontedera Urban Context

The analysis has been applied to the case study town of Pontedera (near Pisa, Tuscany Region, Italy). Pontedera is a medium sized town, with a population of ~30,000 inhabitants. Pontedera has been analysed because represents a typical town with a medieval historical district and an industrial suburb. The town is located near the confluence of the Era River into the Arno River and is bordered by two rivers—the Scolmatore Canal and the Pisa–Florence Railway—and the motorway between Florence, Pisa and Livorno (see Figure 3).

In order to automate the space syntax analysis, the software Depthmap X v.10.14.00b has been used [45]. The input data for the software is the urban street grid of Pontedera in a vector format (dxf file). Software provides outputs such as colour charts and numeric tables which compare the calculated spatial indicators: *I* and *Ch*. Figures 4 and 5 show the axial and the angular segment analyses of the Pontedera urban grid, respectively. *I* and *Ch* are shown with a chromatic scale where blue represents the very lowest values and cyan, green, yellow, orange and, progressively, red represent the very highest value [46].

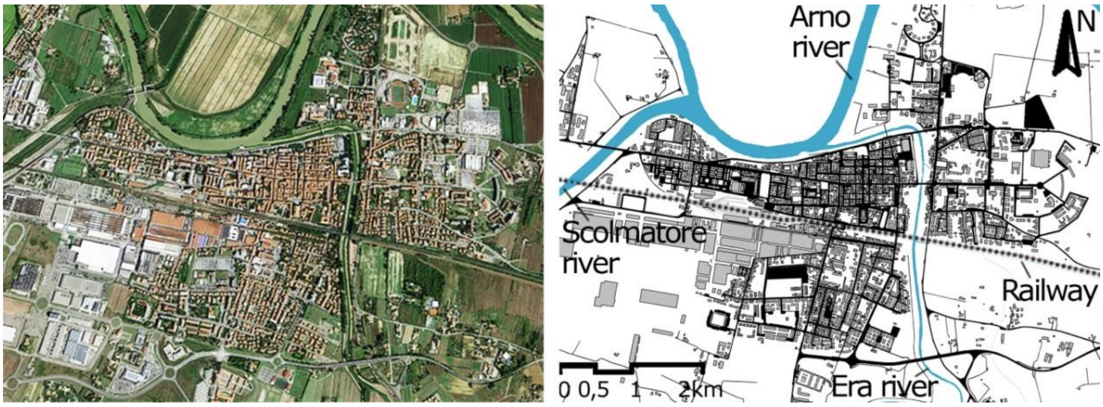


Figure 3. Aerial view of Pontedera (**left**) and schematic representation of its roads (**right**).

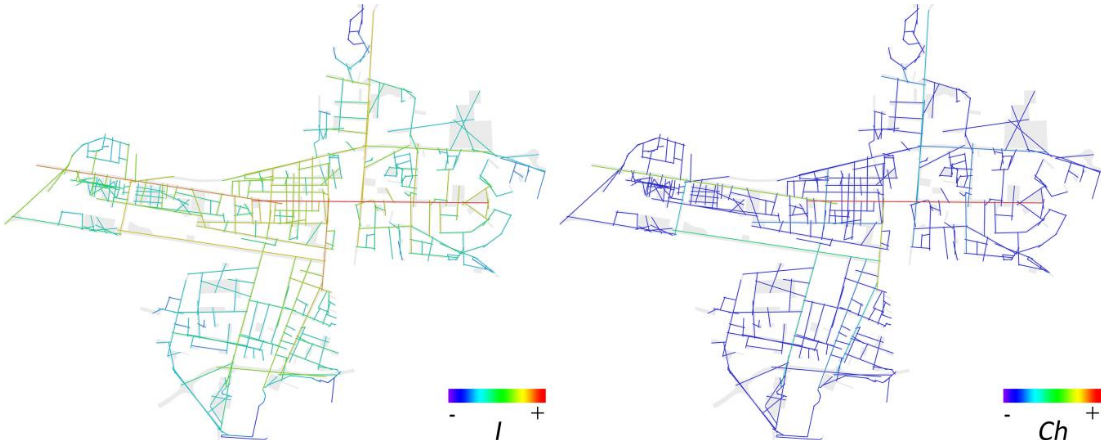


Figure 4. Results of the axial analysis of Pontedera, colour maps of: integration index, *I* (**left**), and choice index, *Ch* (**right**).

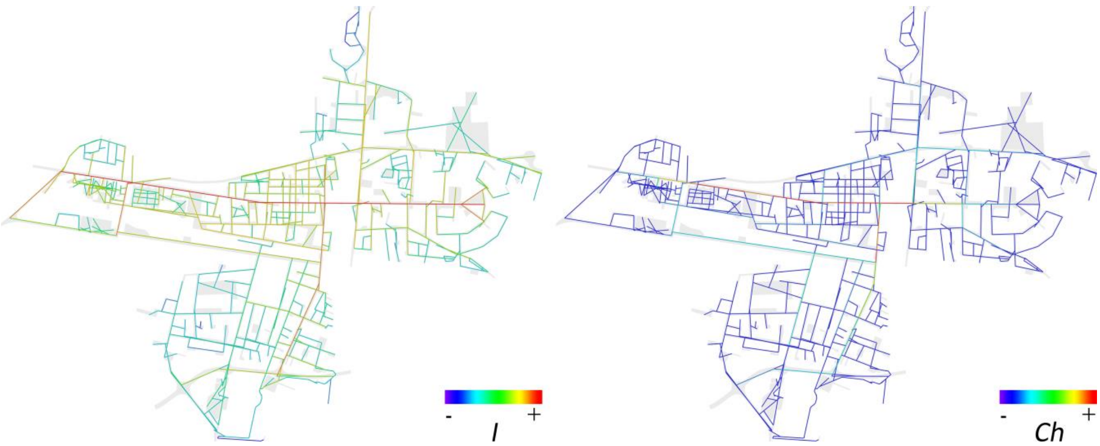


Figure 5. Results of the angular segment analysis of Pontedera, colour maps of: integration index, *I* (**left**), and choice index, *Ch* (**right**).

The Pontedera municipality has defined 305 public roads for its urban context. Using the methods of space syntax analysis, the axial map is composed by 388 axial lines and the angular segment map is composed by 1414 segments. The values of *I* and *Ch* have been calculated for all the lines and segments and then associated to Pontedera public roads. In the association procedure, some roads could be described by several lines/segments (e.g., thinking to roads with curves); therefore, the average values of the spatial indicators of these lines/segments have been associated with the considered road. The minimum value of the *I* index calculated for the axial analysis is 0.56 while the maximum is 2.48. The minimum value of the *Ch* index is 0, the maximum is 79,167. The minimum value of the *I* index calculated for the angular segment analysis is 212, while the maximum is 623. The minimum value of the *Ch* index is 0, the maximum is 433,465. From the graphs of Figures 4 and 5 both for the axial and the angular segment analysis, the traffic volumes distribution inside Pontedera urban context is clear. The maximum intensity of the traffic volumes is in correspondence of the axis that crosses the city from East to West.

2.4. Observation Campaign of Pedestrian and Motorised Traffic

To validate and confirm the results of space syntax analysis, an observation campaign of pedestrian and motorised traffic has been performed on 40 roads (see Figure 6), representative of the roads in the urban context of Pontedera and corresponding to the 13% of all Pontedera roads. The 40 roads have been selected with the help of space syntax analysis. The 305 public roads in Pontedera have been divided in six groups: A—main roads; B—roads of the historical centre; C—secondary roads; D—roads connecting districts; E—access roads to neighbourhoods; and F—neighbourhoods roads. Each group is obtained considering a constant increment, Δ, of the *I* index (from I_{min} to I_{max} with increments of Δ = 0.32), see Table 1. The 40 roads were selected choosing a variable number of roads by each group, so as to reproduce the percentage distribution of the Pontedera public roads in the six groups shown in Table 1. For example, in the "A group" (i.e., Pontedera main roads) there are 37 roads (12.2% of 305); consequently, within the 40 roads, 5 roads have been selected from the "A group" (12.2% of 40).

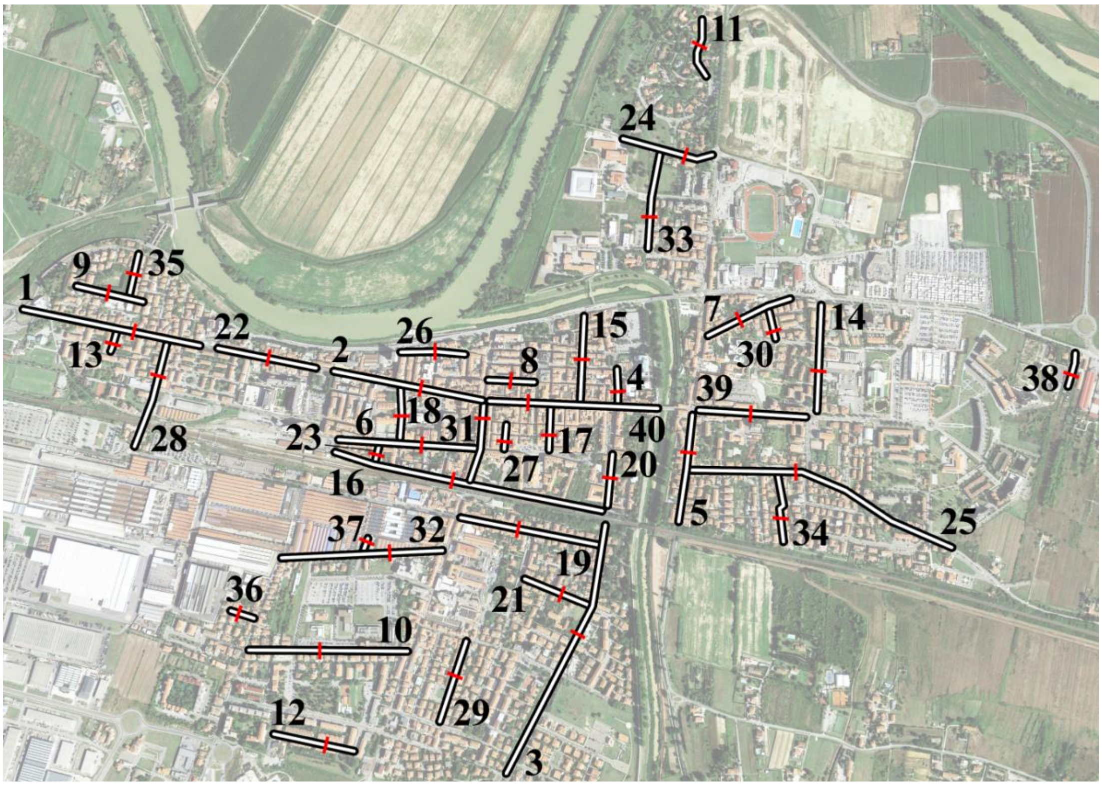


Figure 6. Location of the 40 roads in which the traffic volumes have been observed (the sections adopted for the traffic volumes observations campaign are shown with red lines).

The observation campaign of pedestrian and motorised traffic has been conducted with the gate method: for each road a significant section has been chosen (see Figure 6), far from any perturbative element (e.g., intersections, stops of public transport, entries of companies or shops, construction sites, etc.). For each road section, the number of vehicles and passers-by in 10 min has been observed, in the period of maximum crowding (from 5:30 p.m. to 7:30 p.m.), corresponding to the most difficult condition required by the visual task due to the high traffic volumes. The period of maximum crowding has been determined after an observation of the traffic conditions during night-time from sunset (when the Pontedera street lighting is turned on to sunrise when it is turned off). The traffic observation campaign has been conducted in the month of June 2017 and in Table 2 the results are shown.

Table 1. Range of values of the *I* index for the selection of the 40 roads.

Group	*I*	Number of Roads	Number of Selected Roads
A	$2.48 \leq I \leq 2.16$	37 (12.2%)	5 (12.2%)
B	$2.16 < I \leq 1.84$	38 (12.5%)	5 (12.5%)
C	$1.84 < I \leq 1.52$	69 (22.5%)	9 (22.5%)
D	$1.52 < I \leq 1.20$	46 (15.0%)	6 (15.0%)
E	$1.20 < I \leq 0.88$	76 (25.0%)	10 (25.0%)
F	$0.88 < I \leq 0.56$	39 (12.8%)	5 (12.8%)
	Tot.	305 (100.0%)	40 (100.0%)

Table 2. Results of the traffic observations campaign, with a sample rate of 10 min.

Road ID	Traffic Volumes		Road ID	Traffic Volumes	
	Pedestrian	Motorised		Pedestrian	Motorised
1	85	80	21	18	34
2	183	178	22	45	51
3	60	64	23	7	5
4	69	61	24	17	18
5	104	98	25	23	25
6	21	15	26	24	37
7	36	43	27	12	9
8	91	64	28	12	11
9	23	19	29	12	14
10	38	43	30	13	9
11	29	32	31	20	22
12	33	29	32	16	18
13	20	5	33	21	28
14	28	41	34	15	21
15	49	65	35	10	14
16	14	8	36	4	3
17	80	70	37	17	26
18	23	18	38	3	2
19	6	5	39	4	1
20	17	25	40	8	5

2.5. Correlations between Traffic Volumes and Spatial Indicators

To assess which of the four analysed spatial indicators (*I* and *Ch* for the axial analysis; *I* and *Ch* for the angular segment analysis) best fit the Pontedera traffic volumes, a correlation has been made between traffic volumes data (see Section 2.4) and the values of the four analysed spatial indicators (see Section 2.3). A linear regression analysis has been performed using the least squares method and then calculating the coefficient of determination (R^2). For example, in Figure 7, the correlations between the logarithm values of the pedestrian traffic volumes measured in the 40 roads and the values of the four analysed spatial indicators is shown. The use of the natural logarithm has been adopted on the base of studies conducted on English cities in Nineties [47].

In Table 3, the R^2 coefficient for the correlations between the logarithm values of the pedestrian and motorised traffic volumes observed in the 40 roads and the values of the four analysed spatial indicators are shown. Among the four analysed indicators, the *I* index of the axial analysis has been chosen because it shows the highest R^2 values both in the case of pedestrian and motorised traffic volumes ($R^2 = 0.69$ and $R^2 = 0.59$, respectively).

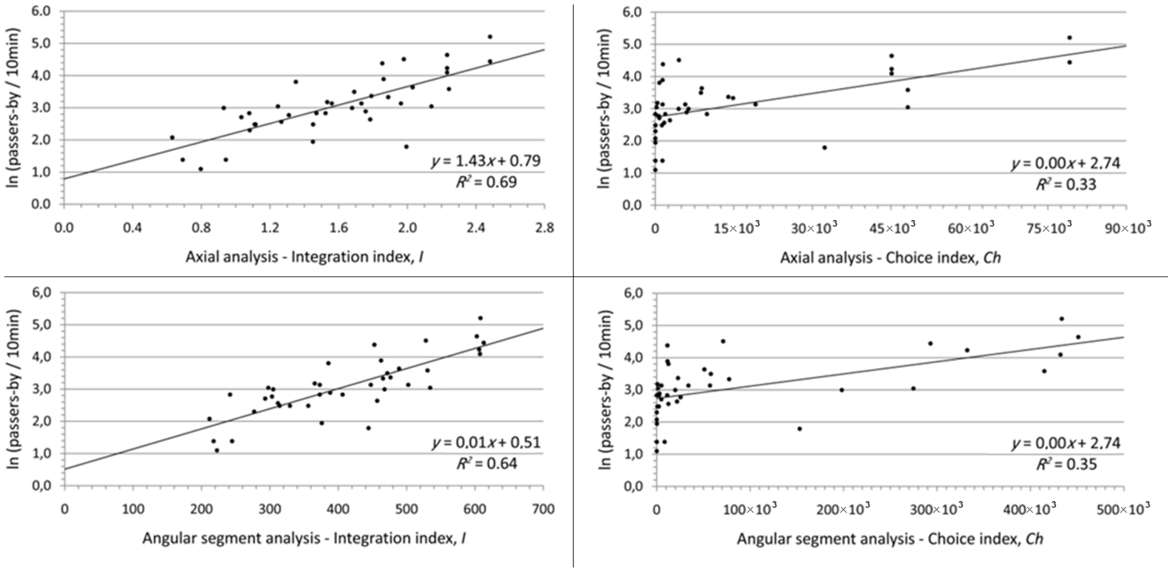


Figure 7. Correlations between the logarithm of the observed traffic volumes for the 40 roads and the four analysed spatial indicators (*I* and *Ch* for the axial analysis; *I* and *Ch* for the angular segment analysis).

Table 3. Comparison of the R^2 coefficients obtained from the correlations between the pedestrian and motorised traffic volumes and the spatial indicators.

Space Syntax Techniques	Spatial Indicators	R^2	
		Pedestrian Traffic Volumes	Motorised Traffic Volumes
Axial analysis	Integration index, *I*	0.69	0.59
	Choice index, *Ch*	0.33	0.29
Angular segment analysis	Integration index, *I*	0.64	0.54
	Choice index, *Ch*	0.35	0.37

3. Analysis of the Lighting Levels for an Urban Context

Lighting parameters to be analysed have been chosen on the basis of the lighting performance requirements established by in force regulations or recommended by specific guidelines. Designers can find the lighting parameters indicated in various technical documents, for example, at international levels, the recommendation CIE 115 [48], and, at the European level, the series of standards 13201 [49–53] at the Italian level the standard [54] or regional regulation [55]. In this research as a reference document the CIE 115 [48] has been chosen. In order to carry out the analysis, two roads for each group described in Table 1 have been selected. The 12 selected roads (see Figure 8) can be considered representative of the total roads of Pontedera because they have been chosen in such a way all the luminaires typologies and arrangement, present in the 305 public roads, are present also in the selected 12 roads.

The minimum lighting requirements have been assessed selecting the appropriate lighting class for every road area (i.e., road areas have been identified in relation to the expected traffic type). The lighting class has been selected in function of the visual tasks of road users following the procedure described by International recommendations [48].

In Table 4, the results of the lighting class selection procedure for the 12 analysed roads are shown together with the recommended minimum lighting requirements. In particular, they following have been selected; the minimum average maintained luminance on carriageways ($L_{av,ref}$, cd/m^2), the minimum average horizontal maintained illuminance ($E_{h,av,ref}$, lx) and the minimum horizontal maintained illuminance ($E_{h,min,ref}$, lx) on sidewalks. Road geometry, luminaires arrangements and luminaires photometric data of the 12 analysed roads have been acquired after a survey campaign in the roads (see Table 5 for road geometry and luminaires arrangements data; see Table 6 for luminaires photometric data).

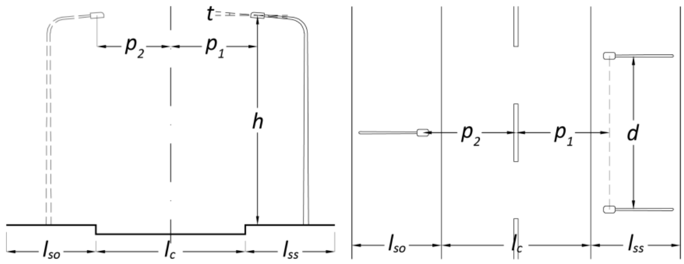
Figure 8. Pontedera roads involved in software simulation; for each road the ID number, the road group (see Table 1) and the integration index value, I, are indicated.

Table 4. Lighting classes and minimum lighting requirements for the 12 selected roads.

Road ID	Lighting Class		Minimum Lighting Requirements		
	Carriageway	Sidewalk	Carriageway	Sidewalk	
			$L_{av,ref}$ [cd/m^2]	$E_{h,av,ref}$ [lx]	$E_{h,min,ref}$ [lx]
1	M3	P3	1.0	5.0	1.0
2	M3	P3	1.0	5.0	1.0
3	M3	P5	1.0	3.0	0.6
4	M3	P5	1.0	3.0	0.6
5	M3	P5	1.0	3.0	0.6
6	M3	P5	1.0	3.0	0.6
7	M3	P5	1.0	3.0	0.6
8	M3	P5	1.0	3.0	0.6
9	M4	P6	0.8	2.0	0.4
10	M3	P5	1.0	3.0	0.6
11	M5	P6	0.5	2.0	0.4
12	M4	P6	0.8	2.0	0.4

Table 5. Road geometric characteristics and luminaires arrangements data for the 12 analysed roads at the present status. The following symbols are used; ID: road identification number; r: road length; l_c: carriageway width; l_{ss}: sidewalk on the same side of the luminaires width; l_{so}: sidewalk on the opposite side of the luminaires width; i: luminaires arrangement type; p_1 and p_2: luminaires position with respect the centre of the carriageway; L_{ID}: luminaires identification letter (see Table 6); d: luminaires distance; h: luminaires height; t: tilt angle of the luminaires; n: luminaires number.

ID	r [m]	l_c [m]	l_{ss} [m]	L_{so} [m]	i	p_1 [m]	p_2 [m]	L_{ID}	d [m]	h [m]	t [°]	n
1	466	7.00	3.45	–	one sided	3.95	–	A	33.50	10.50	15	13
2	431	5.50	3.10	1.80	two sided staggered	3.40	3.60	B	24.00	8.00	5	31
3	735	10.00	3.00	–	one-sided	6.15	–	C	25.00	8.00	0	30
4	109	5.60	1.00	0.60	one-sided	2.80	–	D	18.00	7.50	15	6
5	350	8.00	1.45	1.45	one-sided	4.45	–	A	41.00	12.00	5	7
6	408	12.20	1.50	2.50	one-sided	6.25	–	E	20.50	8.00	15	21
7	295	8.30	1.45	1.45	one-sided	4.45	–	A	24.10	8.00	5	10
8	337	7.00	1.20	1.00	one-sided	3.55	–	F	22.50	9.00	15	13
9	204	7.00	0.90	0.90	one-sided	4.20	–	G	22.00	6.00	15	8
10	442	7.00	2.40	2.40	two sided staggered	4.70	5.70	H	50.00	7.00	5	18
11	241	3.50	1.00	1.00	one-sided	2.45	–	I	12.00	3.50	0	19
12	111	6.75	1.60	1.60	two sided staggered	3.78	3.78	G	40.00	6.00	0	5

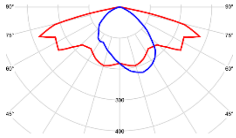
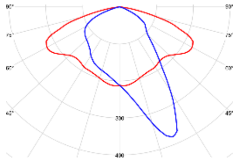
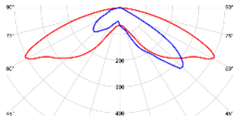
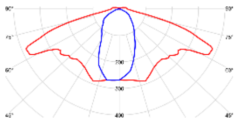
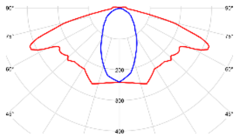
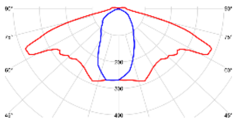
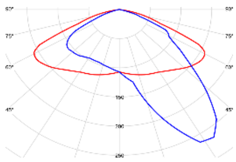
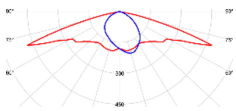
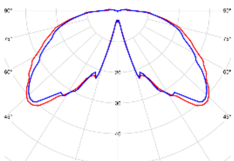


3.1. In Situ Measurements of the Lighting Parameters

A measurement campaign of the lighting parameters has been conducted on the 12 analysed roads. The horizontal illuminance on sidewalks and the luminance on carriageway in both directions have been measured on each road. An adequate measurement grid has been set up by identifying the minimum number of points where illuminance and luminance have been subsequently measured. For each typical span, five points have been identified for the horizontal illuminance measurements on each sidewalk and six points for the luminance measurements on the carriageway. In Figure 9, an example of the illuminance and luminance measurement grid for one of the 12 roads is shown. With the aim of verifying the repeatability of the measurement results, the horizontal illuminance and luminance measurements have been repeated 3 times for the 20% (randomly selected) of the total measured points, obtaining a maximum deviation between measures taken at the same point equal to 8%. This deviation, in relation to the type of measurements made (i.e., illuminance and luminance values due to road lighting systems), is such that no significant variations on the results obtained have been introduced.

The photometric instruments, used in the measurements campaign, have been selected among those available at the Lighting and Acoustics Laboratory of the University of Pisa, according to the selection criteria indicated in European standards [52]. For the illuminance measurements, the lux meter Delta Ohm mod.2101.2 has been used, equipped with the probe mod.LP471PHOT for horizontal illuminance measurements. The lux meter allows illuminance measurements from 1 lx to 2×10^4 lx, with mismatch of spectral responsivity ($f_1{}'$) and deviation from cosine response law (f_2), evaluated according to International standards [56], lower than 6% and 3% respectively. For the luminance measurements, the luminance meter *Hagner mod.S4* has been used, equipped with a silicon photodiode detector. The luminance meter allows luminance measurements (1° of measuring angle) from 1×10^{-2} cd/m^2 to 2×10^5 cd/m^2, with $f_1{}'$ and f_2 values lower than 3% and 1.5% respectively.

Table 6. Photometric data of the luminaires at the present status. The following symbols are used; L_{ID}: luminaires identification letter; *P*: luminaire power; *Φ*: luminaire luminous flux; *η*: luminaire efficacy; S: source type; T_c: correlated colour temperature; HPS: High Pressure Sodium; MH: Metal Halide; LED: light-emitting diode.

L_{ID}	*P* [W]	*Φ* [lm]	*η* [lm/W]	S	T_c [K]	Photometry	Image
A	166	13,194	79	HPS	2000		
B	158	10,897	69	MH	3000		
C	118	6099	52	LED	4200		
D	114	7546	66	HPS	2000		
E	169	11,412	68	MH	3000		
F	114	6700	59	MH	4200		
G	157	9988	64	MH	3000		
H	118	6099	52	MH	4200		
I	116	2430	21	HPS	2100		

For each analysed road, the average horizontal value and the minimum horizontal value of the illuminance have been calculated on the sidewalks ($E_{h,av}$, lx); while the average luminance value

(L_{av}, cd/m^2) for the carriageways has been calculated. The measurements results are shown in Table 7 for the 12 analysed roads. It must be noted that, among the 12 analysed roads, six roads (roads 1, 2, 3, 5, 7 and 8) are not in compliance with the minimum lighting requirements shown in Table 4. In addition, if the energy consumptions are considered the following considerations can be made. The 77% of roads have a luminaire type with an energy class not adequate, i.e., the energy class is less than the minimum value according to the energy classification introduced by the local regulation of Emilia-Romagna Region (see Appendix A). Ninety-two percent of lighting systems of the carriageways have an energy class that is not adequate (see Appendix A). On average, the lighting systems of the 12 analysed roads consume 6.0×10^{-2} W/m^2, while the installed luminaires produce, on average, 6.3×10^{-3} lx/m^2 on road surfaces. The road that consumes the most is the ID 4 with 14.5×10^{-2} W/m^2; while the most energy efficient is the ID 3 with 1.2×10^{-2} W/m^2. The road with the best production of average illuminance values per square meter is the ID 4 with 28.3×10^{-3} lx/m^2, while the least performing road is the ID 3 with 1.6×10^{-3} lx/m^2.

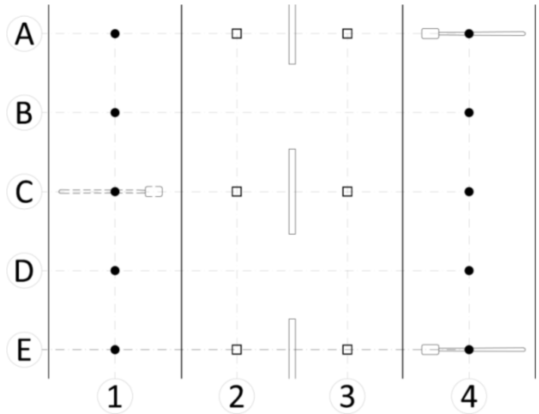


Figure 9. Grid adopted for measurements of illuminance and luminance values. The following symbols are used; ● (black dot): illuminance measurement point; □ (white square): luminance measurement point.

Table 7. Results of the measurements survey for the 12 analysed roads (present status). The luminance and illuminance values are expressed with measurement tolerances of ±0.05 cd/m^2 and ±0.05 lx, respectively.

Road ID	Carriageway	Sidewalk (on Luminaire Side)		Sidewalk (on the Opposite Luminaire Side)	
	L_{av} [cd/m^2]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]
1	0.7	21.4	11.9	–	–
2	0.9	8.6	4.9	6.6	3.8
3	0.9	13.9	11.5	–	–
4	1.9	21.3	12.3	10.6	8.3
5	0.6	6.7	3.5	7.4	5.2
6	1.1	12.1	6.0	3.7	2.6
7	0.8	10.0	5.8	6.3	5.8
8	0.5	10.4	6.4	4.7	3.5
9	0.8	12.4	5.6	13.0	10.9
10	1.2	13.3	6.4	12.8	5.6
11	0.6	9.1	3.3	5.0	3.3
12	1.2	11.0	5.5	10.8	5.9

3.2. Software Simulations of the Lighting Parameters at the Present Status and Validation of the Model

Lighting parameters calculation in software simulations has been conducted in accordance with EN 13201-3 and EN 13201-4 [51,52]. Software simulations have been carried out with the help of DIALux software [57] by modelling road geometry and luminaires arrangements. Photometric data of the luminaires have been implemented in the software thanks to EULUMDAT photometric files. Given the absence of a municipal maintenance planning in Pontedera, simulations have been carried out by estimating the maintenance factors according to international recommendations [58].

In Table 8, the lighting parameters resulting from software simulations are shown. In Figure 10, false-colour renderings of the horizontal illuminance mapping for six roads (one for each group of Table 1) are shown. Software outputs have been validated comparing simulated values with in situ measured ones. In Table 8, for every simulated value, the percentage deviations between the simulated and the measured values are shown, such deviations are always less than 15%. The simulated values appear to be cautionary with respect to in situ measured ones. The mean percentage of deviations between measured and simulated values is 8.2%.

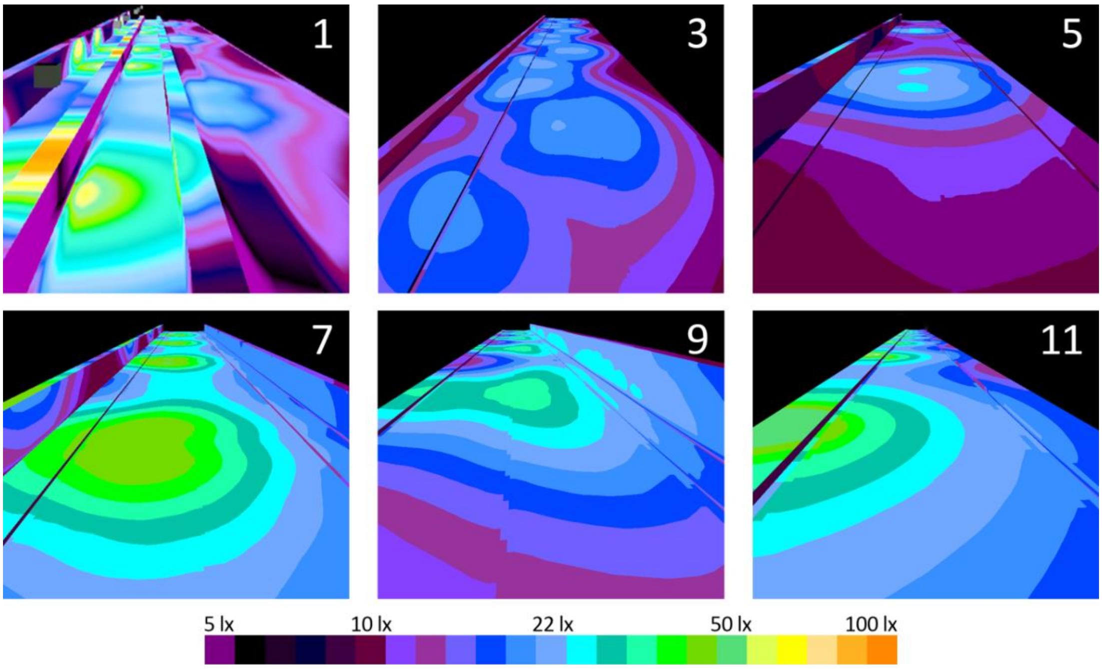


Figure 10. False-colour renderings of the horizontal illuminance mapping for some analysed roads at the present status (one for each group of Table 1).

Table 8. Results of the software simulation at the present status for the considered lighting parameters. For each parameter the percentage deviations between measured (see Table 7) and simulated values are also indicated. The luminance and illuminance values are expressed with three digits.

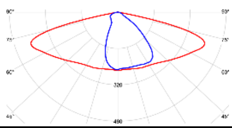
Road ID	Carriageway		Sidewalk (on Luminaire Side)				Sidewalk (on the Opposite Luminaire Side)			
	L_{av} [cd/m^2]	(%)	$E_{h,av}$ [lx]	(%)	$E_{h,min}$ [lx]	(%)	$E_{h,av}$ [lx]	(%)	$E_{h,min}$ [lx]	(%)
1	0.72	3	23.8	11	13.1	10	–	–	–	–
2	0.98	9	9.09	6	5.24	7	7.44	13	3.97	4
3	0.96	7	15.6	12	11.7	2	–	–	–	–
4	1.98	4	22.2	4	14.0	14	11.5	8	9.12	10
5	0.67	12	7.33	9	3.68	5	8.00	8	5.80	12
6	1.27	15	13.7	13	6.74	12	4.08	10	2.63	1
7	0.86	7	11.2	12	6.32	9	6.88	9	6.06	4
8	0.57	14	10.7	3	6.46	1	4.90	4	3.80	9
9	0.91	14	13.3	7	5.88	5	14.8	14	12.3	13
10	1.38	15	13.6	2	6.56	2	13.6	6	6.11	9
11	0.60	0	9.72	7	3.46	5	5.20	4	3.51	6
12	1.36	13	12.3	12	6.06	10	12.3	14	6.06	3

3.3. Software Simulation of the Lighting Parameters at the Design Status and Refurbishment Project

The refurbishment project of the lighting systems has been developed, for the analysed roads, following a three-phase methodology. In the first phase, the lighting systems of the selected roads are analysed at the present conditions evaluating their energy efficiency and compliance with minimum lighting requirements. In the second phase, a refurbishment project of the lighting systems is developed improving the energy efficiency and compliance with lighting standards requirements. In the third phase, the economic feasibility of the refurbishment project is evaluated. The methodology is well described in recent researches by Beccali et al. [59,60]. The methodology adopted for the refurbishment project ensures the respect of the lighting parameters related to safety and visual comfort tasks, the improvement of the environmental sustainability of the lighting systems and the economic feasibility of the project itself. In particular, the refurbishment project has intended to pursue the following objectives; improve the energy efficiency of the lighting systems and of the luminaires and select design options with a good payback time of the investments needed for the project.

In general, during the design phase the arrangements and the heights of installation of the luminaires has not been changed due to investment cost reduction reasons (also following the specific solicitations from Pontedera municipality); in some cases, with the aim of improving road safety and lighting systems energy efficiency, it has been necessary to change the luminaires distances. The new adopted luminaires use LED technologies and are in the maximum energy class (A^{++}), according to the local regulation of Emilia-Romagna Region (see Appendix A). The adopted luminaires for the 12 analysed roads are shown in Table 9. In the refurbishment project, the design options requiring the lowest initial economic investment have been the priority. Therefore, the first design option has been to replace the obsolete luminaires with new ones, the second design option has been to modify luminaire arrangements (also accepting consequent increasing of the initial economic investment). At the design status, the replacement of obsolete luminaires in 10 roads, with new ones more efficient, has been considered. Furthermore, it has been necessary to change the arrangement of the luminaires installation in two roads (ID 1 and ID 10 roads), to meet at least some of the minimum lighting requirements. Such minimum requirements are not achieved in all the 12 roads, since it is not simple to meet these requirements with the imposed constraints of the installation arrangement.

Table 9. Photometric data of the luminaires at the design status. The following symbols are used; L_{ID}: luminaires identification letter; *P*: luminaire power; *Φ*: luminaire luminous flux; *η*: luminaire efficacy; S: source type; T_c: correlated colour temperature; LED: light-emitting Diode.

L_{ID}	*P* [W]	*Φ* [lm]	*η* [lm/W]	S	T_c [K]	Photometry	Image	Road of Installation (ID Number)
L	138	14,663	106	LED	4000			1, 5
M	63	7083	112	LED	4000			3, 7, 8, 12
N	56	5742	103	LED	4000			2, 6, 10
O	32	3305	103	LED	4000			4, 9, 11

In Table 10, the lighting parameters resulting from software simulations at the design status are shown. In Figure 11, false-colour renderings of the horizontal illuminance mapping for six roads (the same shown in Figure 10) are shown. At the design status, the lighting systems of all carriageways meet the minimum energy class prescribed by Emilia-Romagna Region (see Appendix A).

Table 10. Results of the software simulation at the design status for the considered lighting parameters. The luminance and illuminance values are expressed with three digits.

Road ID	Carriageway	Sidewalk (on Luminaire Side)		Sidewalk (on the Opposite Luminaire Side)	
	L_{av} [cd/m^2]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]
1	1.03	21.4	13.2	–	–
2	1.24	17.5	10.7	13.2	5.75
3	1.08	15.7	3.93	–	–
4	1.06	12.4	9.02	9.34	8.76
5	1.07	13.9	7.11	12.4	10.2
6	1.02	14.0	9.49	8.66	6.93
7	1.02	11.8	5.07	9.51	8.50
8	1.00	12.3	11.5	9.56	10.5
9	0.77	11.2	5.16	3.69	3.05
10	1.00	9.82	4.45	9.82	4.45
11	0.60	15.4	4.66	4.49	2.90
12	0.86	8.62	3.05	8.62	3.05

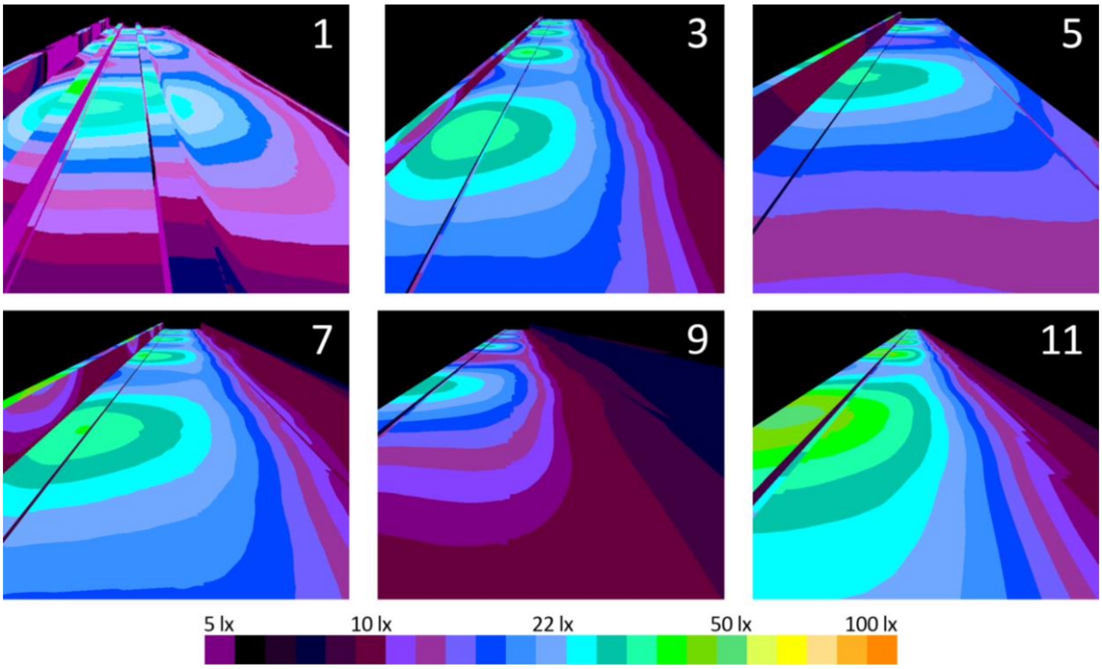


Figure 11. False-colour renderings of the horizontal illuminance mapping for some analysed roads at the design status (one for each group of Table 1).

4. Correlations between Spatial Indicators and Lighting Parameters

The correlations have been obtained adopting the *I* index of the axial analysis (see also Sections 2.2 and 2.3). The choice of this spatial indicator has been made because it shows the best goodness-of-fit with respect to the observed traffic data, as demonstrated in Section 2.5. This spatial indicator has been correlated with the main lighting parameters: the average maintained luminance in the carriageways (L_{av}), the average maintained illuminance ($E_{h,av}$) and the minimum maintained illuminance ($E_{h,min}$) on the sidewalks. These lighting parameters have been measured and calculated for the 12 analysed roads (see Section 3). The correlations between *I* index and lighting parameters are found by means a linear regression analysis performed using the least squares method. The used lighting parameters are: those measured at the present status (in this Section named Scenario 1), those calculated at the design status (in this Section named Scenario 2) and those given by the European technical standards as minimum lighting requirements values (ideal case, in this Section named Scenario 3).

4.1. Correlations in the Case of Scenario 1 (Present Status)

In Figure 12, the correlation between the I index and L_{av} is shown. In this case, the R^2 coefficient is negligible and the data are very scattered with respect to the regression line. However, the regression line slope suggests that as roads centrality increases, luminance values slightly increase as if roads of the centre need more light.

In Figure 13, the correlation between the I index and $E_{h,av}$ is shown (black circles) together with the correlation between the I index and $E_{h,min}$ (white circles) for the sidewalks on the same side of luminaires. In both cases the R^2 coefficients are low and they results: R^2 = 0.16 (in the case of $E_{h,av}$) and R^2 = 0.33 (in the case of $E_{h,min}$). The regression lines have a positive slope showing an increase of the illuminance values as roads centrality increases. The positive slopes suggest that the town centre is more enlightened while its suburb appears less enlightened. This is a normal and expected course because generally to the most central roads correspond the greater traffic volumes.

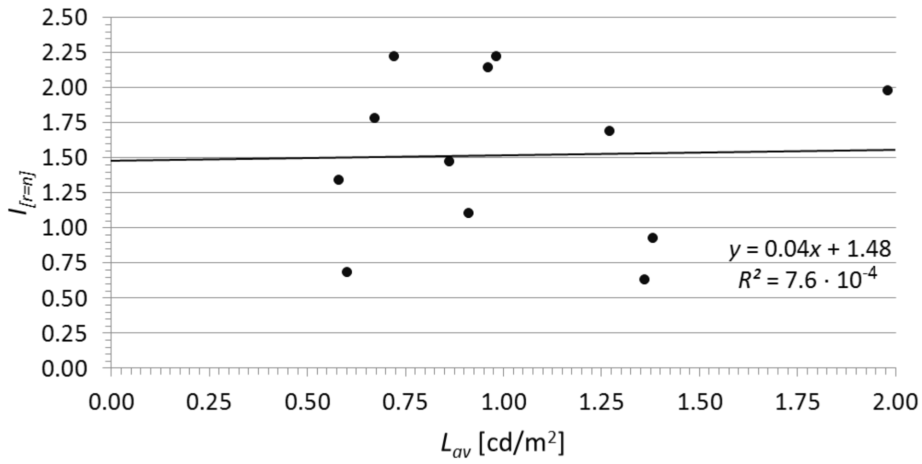


Figure 12. Scenario 1 (present status): correlation between I and L_{av}.

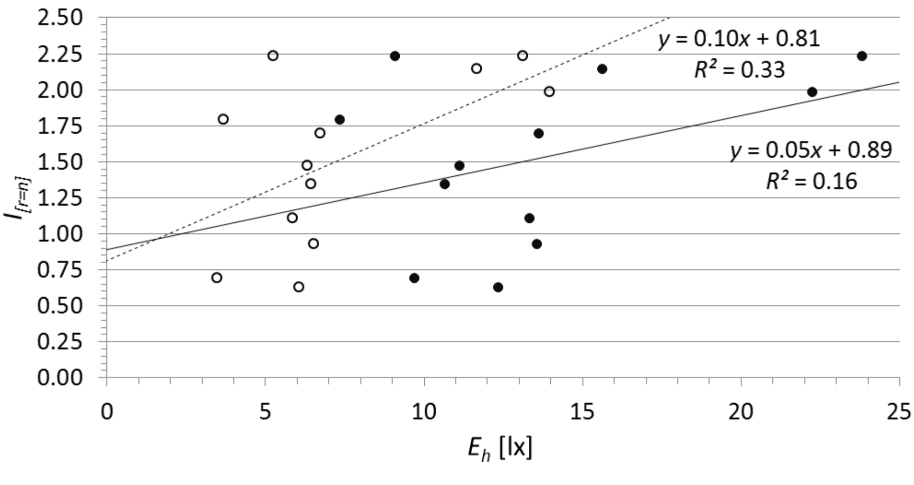


Figure 13. Scenario 1 (present status): correlations between I and $E_{h,av}$ (black circles and a continuous line for the regression) and between I and $E_{h,min}$ (white circles and a dotted line for the regression) on the sidewalks on the same side of luminaires.

In Figure 14, the correlations between the I index is shown (black circles) together with the correlation between the I index and $E_{h,min}$ (white circles) for the sidewalks on the opposite side of luminaires. In both cases the R^2 coefficients are negligible. The regression line slopes are negative in both cases showing a trend that is the inverse of the illuminance values on sidewalks on the same side of luminaires. The negative slopes of the regression lines suggest that as roads centrality increases, illuminance levels on sidewalk on the opposite side of luminaires decrease as if roads of the centre are less enlightened. This is an unexpected result because minimum lighting requirements are the same for both the sidewalks and they increase as roads centrality increases.

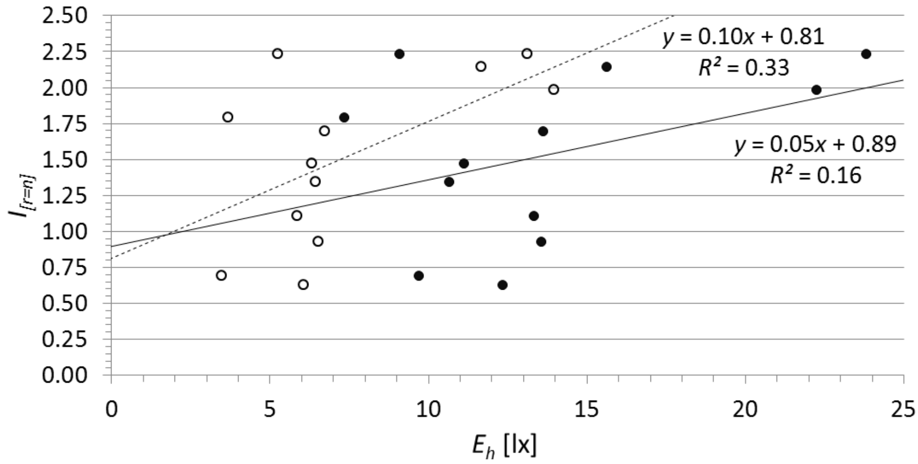


Figure 14. Scenario 1 (present status): correlations between I and $E_{h,av}$ (black circles and a continuous line for the regression) and between I and $E_{h,min}$ (white circles and a dotted line for the regression) on the sidewalks on the opposite side of the luminaires.

4.2. *Correlations in the Case of Scenario 2 (Design Status)*

In Figure 15, the correlation between the I index and L_{av} at the design status (see Section 3.3) is shown. In this case, compared to the present status (see Figure 12), R^2 increases from a negligible value to 0.63. The regression line slope is positive suggesting that as roads centrality increases, luminance levels increase because more trafficked roads need to be more enlightened. The R^2 coefficients increase also for the correlations between I index and both $E_{h,av}$ and $E_{h,min}$.

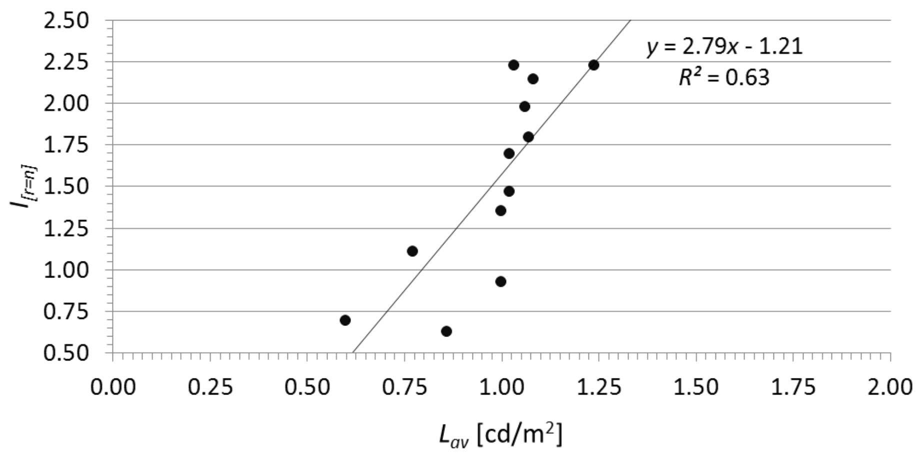


Figure 15. Scenario 2 (design status): correlation between I and L_{av}.

Looking at the sidewalks on the same side of luminaires (see Figure 16), for $E_{h,av}$, R^2 varies from 0.16 (see Figure 13) to 0.48; while for $E_{h,min}$, R^2 varies from 0.33 (see Figure 13) to 0.39. The slopes of the regression lines are positive so for more central roads the illuminance levels increase. Looking at the sidewalks on the opposite side of luminaires (see Figure 17), it can be observe that, for $E_{h,av}$, R^2 varies from 0.08 (see Figure 14) to 0.43; while for $E_{h,min}$, R^2 varies from a negligible value (see Figure 14) to 0.41. The slope of the regression lines is positive so for more central roads the illuminance levels increase.

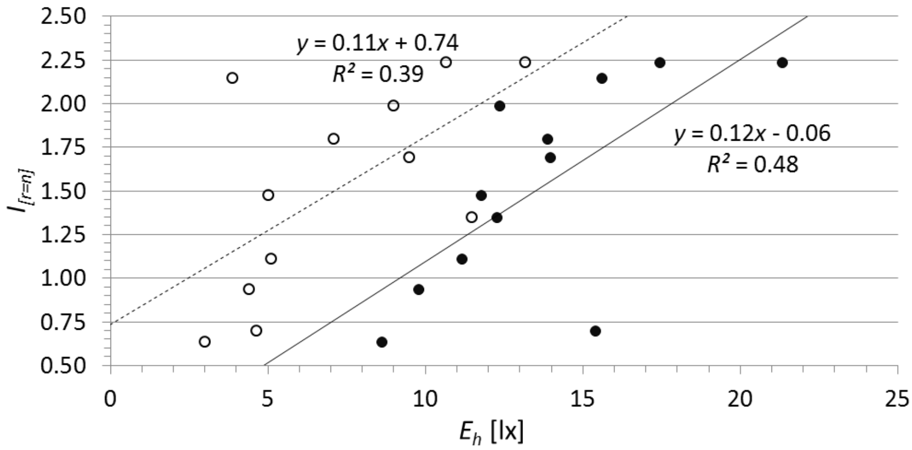


Figure 16. Scenario 2 (design status): correlations between I and $E_{h,av}$ (black circles and a continuous line for the regression) and between I and $E_{h,min}$ (white circles and a dotted line for the regression) on the sidewalks on the same side of luminaires.

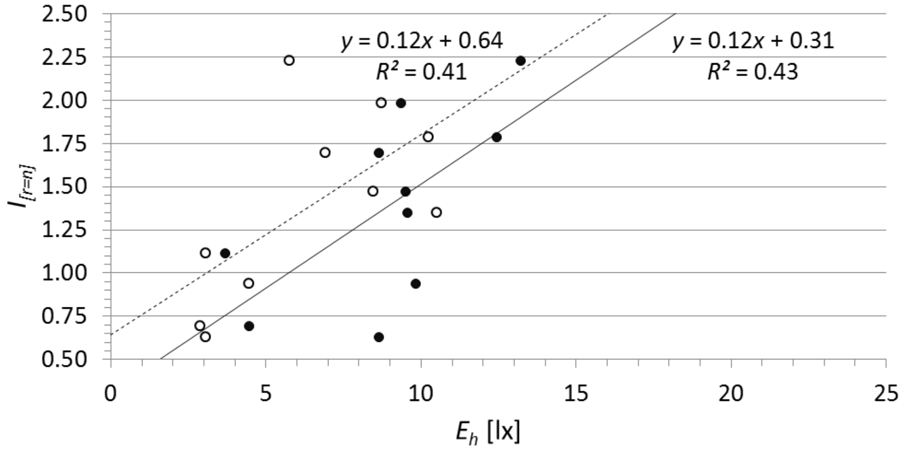


Figure 17. Scenario 2 (design status): correlations between I and $E_{h,av}$ (black circles and a continuous line for the regression) and between I and $E_{h,min}$ (white circles and a dotted line for the regression) on the sidewalks on the opposite side of the luminaires.

4.3. Correlations in the Case of Scenario 3 (Ideal Case)

Finally, the correlations has been analysed considering the ideal case in which roads are enlightened exactly with the values of the minimum lighting requirements (see for example Table 4). In this case, compliance with the minimum lighting requirements is imposed considering an ideal configuration without specifying photometric data of the luminaires and arrangements characteristics of the lighting systems. Obviously, the minimum lighting requirements have been established on the basis of the lighting classes of roads, selected with the standard procedure [48].

In Figure 18, the correlation between the I index and the minimum average maintained luminance ($L_{av,ref}$) for carriageways is shown. In Figure 19, correlations between the I index and the minimum average maintained illuminance ($E_{h,av,ref}$) for sidewalks, and between the I index and the minimum maintained illuminance ($E_{h,min,ref}$) are shown. In each of the three cases the R^2 are higher than before. It is possible to observe that the R^2 increases from 0.63 (see Figure 15) to 0.67, in the case of L_{av}. If the sidewalks on the same side of the luminaries are considered, the R^2 increase from 0.39 (see Figure 16) to 0.57, in the case of $E_{h,min}$, and from 0.48 (see Figure 16) to 0.53, in the case of $E_{h,av}$.

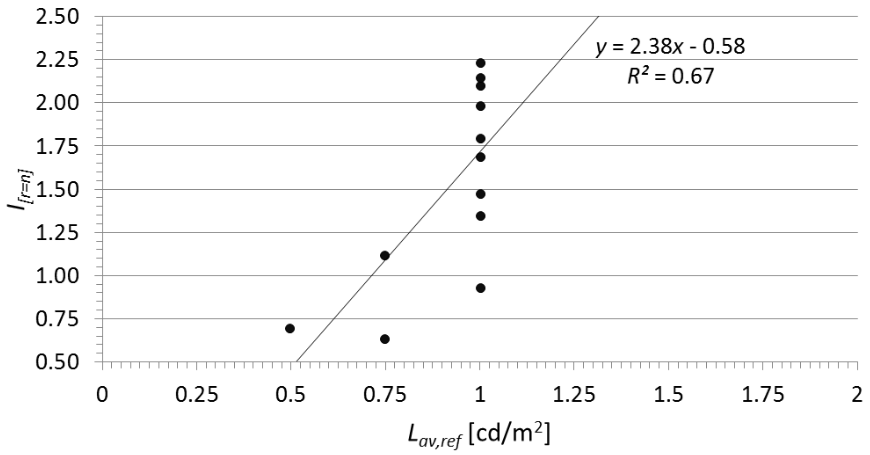


Figure 18. Scenario 3 (ideal case): correlation between I index and $L_{av,ref}$.

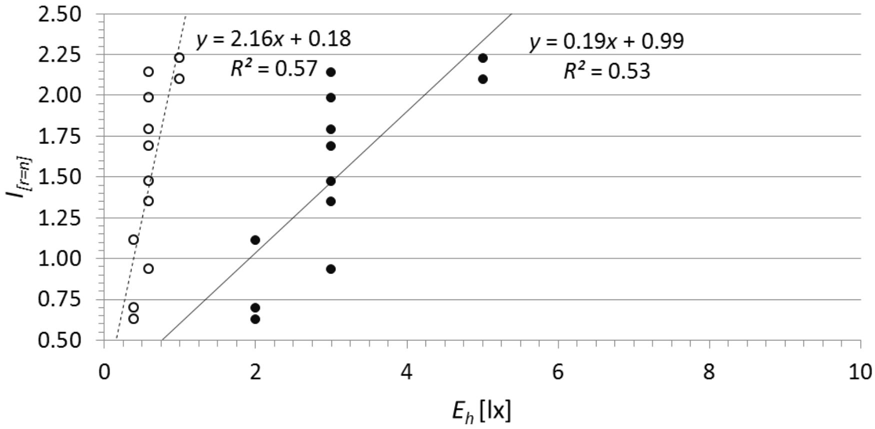


Figure 19. Scenario 3 (ideal case): correlations between I and $E_{h,av,ref}$ (black circles and a continuous line for the regression) and between I and $E_{h,min,ref}$ (white circles and a dotted line for the regression) on the sidewalks on the opposite side of the luminaires.

5. Discussion and Conclusions

In this paper, the authors mainly dealt with analysing the correlations between spatial properties and lighting levels in order to obtain useful information for the early design stage of lighting systems in urban context.

At the present status (Scenario 1), for all the correlations, the R^2 values are not significant. In other words, there is no relationship linking traffic conditions expressed by the I index to the lighting levels in the analysed roads. It should be noted that, at the present status, many lighting systems of the roads are not in compliance with the recommended minimum lighting requirements and all the lighting systems are characterised by poor energy performance.

At the design status (Scenario 2), an increase of the R^2 values in the correlations has been observed. The chosen design options, following the step-by-step methodology proposed in recent researches by the authors [11,59,60], guarantee that the lighting parameters are adjusted on the real traffic conditions. Therefore, with road lighting systems that are well-designed in more trafficked and central roads with more restrictive lighting requirements are expected higher illuminance levels than peripheral and less trafficked roads. For all the correlations of Scenario 2, R^2 values increase with respect to the cases of the Scenario 1 and the correlations between spatial properties and lighting levels is stronger. For example (see Table 11), the R^2 values vary as follows: from a negligible value to 0.63 for luminance correlations on carriageways; from 0.16 to 0.48 for the average horizontal illuminance correlations on sidewalks, on the same side of luminaires; from 0.08 to 0.43 for the average horizontal illuminance correlations on sidewalks, on the opposite side of luminaires; similar increments of R^2 values can be observed for the minimum maintained horizontal illuminance. In other words, traffic volumes assessed by the *I* index are able to influence the lighting levels.

Table 11. Comparison of the coefficient of determination R^2 in the three scenarios (between brackets the percentage increments of R^2 with respect to the Scenario 1 is shown).

Scenario	Carriageway	Sidewalk (on Luminaire Side)		Sidewalk (on the Opposite Luminaire Side)	
	L_{av} [cd/m^2]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]	$E_{h,av}$ [lx]	$E_{h,min}$ [lx]
1 (present status)	7.6×10^{-4}	0.16	0.33	0.08	4.7×10^{-3}
2 (design status)	0.63 (63%)	0.48 (32%)	0.39 (6%)	0.43 (35%)	0.41 (41%)
3 (ideal case)	0.67 (67%)	0.53 (37%)	0.53 (20%)	0.53 (45%)	0.53 (53%)

At the ideal case (Scenario 3) the highest R^2 values have been found. In fact, the correlations show R^2 values of 0.67 for luminance values and 0.53 for illuminance values (see Table 11). The R^2 values for luminance correlations on carriageways increases of the 4% with respect to the Scenario 2 and of the 67% with respect to the Scenario 1. The R^2 values for $E_{h,av}$ correlations on sidewalks on the luminaire side increase by 5% with respect to Scenario 2 and by 37% with respect to Scenario 1 (10% with respect to Scenario 2 and 45% with respect to Scenario on sidewalks on the opposite luminaire side). Increments up to 20%, with respect to Scenario 2 and up to 53% with respect to Scenario 1, have been observed for the minimum maintained horizontal illuminance. It is important to note that in the Scenario 3 the roads are enlightened exactly with the values of minimum lighting requirements. The ideal case of Scenario 3, which is not always realisable in real cases, is characterised by the best energy performance. The higher values of R^2 confirm that correlations become stronger as luminance and illuminance values tend to the recommended minimum lighting requirements and as the energy efficiency of the lighting systems increase.

The presence of the discussed correlations lays the foundations for a change in the lighting design approaches on urban scale. In light of what has been verified by the authors, the preliminary phases of the lighting design could be placed side by side with the urban planning phases (not postponed after, as generally happens). In fact, by exploiting the correlations between spatial indicators and lighting parameters, it will be possible to set in advance the lighting requirements that lighting systems will have to satisfy for each road, without the use of specific methods for roads classification based on the traffic volumes (usually expensive if traffic observation campaigns are adopted). As clearly described, the correlations have been analysed for a single case study; verifications of these correlations, on an experimental basis conducted by different research groups, will be useful to obtain confirmation of what has been found and to generalise the results obtained in this research.

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Appendix A

The Emilia Romagna Region local regulation [55] is a useful tool for energy classification of luminaires and street lighting systems.

According to the energy classification introduced by the local regulation of Emilia Romagna, the energy classes of the luminaires can be evaluated in function of the *IPEA* (Luminaire Energy Efficiency Indicator) values. The energy class of a luminaire can be selected on the base of Table A1. The minimum class required by the Emilia Romagna regulation is the class C. The *IPEA* indicator can be calculated with the following equation.

$$IPEA = \eta_l \cdot \eta_s \cdot D_{lor}$$

where η_l is the luminous efficacy of the lamp, η_s is the power supply efficacy (ratio between the lamp nominal power and the input power supply) and D_{lor} is the ratio between the luminous flux emitted downwards by the luminaire and the total luminous flux emitted by the lamps.

Table A1. (left) Energy classes for luminaires in function of the *IPEA* indicator (in grey the minimum class required in Emilia Romagna Region). (right) Energy classes for lighting systems in function of the *IPEI* indicator (in grey the minimum class required in Emilia Romagna Region).

IPEA Class	*IPEA* Value	*IPEI* Class	*IPEI* Value
A^{++}	$1.15 < IPEA$	**A^{++}**	$IPEI < 0.75$
A^{+}	$1.10 < IPEA \leq 1.15$	**A^{+}**	$0.75 \leq IPEI \leq 0.82$
A	$1.05 < IPEA \leq 1.10$	**A**	$0.82 \leq IPEI \leq 0.91$
B	$1.00 < IPEA \leq 1.05$	**B**	$0.91 \leq IPEI \leq 1.09$
C	$0.93 < IPEA \leq 1.00$	**C**	$1.09 \leq IPEI \leq 1.35$
D	$0.84 < IPEA \leq 0.93$	**D**	$1.35 \leq IPEI \leq 1.79$
E	$0.75 < IPEA \leq 0.84$	**E**	$1.79 \leq IPEI \leq 2.63$
F	$0.65 < IPEA \leq 0.75$	**F**	$2.63 \leq IPEI \leq 3.10$
G	$IPEA \leq 0.65$	**G**	$3.10 \leq IPEI$

According to the energy classification introduced by the local regulation of Emilia Romagna, the energy classes of the lighting systems designed on the basis of illuminance can be evaluated in function of the $IPEI_E$ (Lighting system Energy Efficiency Indicator) values while the lighting systems designed on the basis of luminance can be evaluated in function of the $IPEI_L$. The energy class of a lighting system can be selected on the base of Table A1. The minimum class required by the Emilia Romagna regulation is the class B. The IPEI indicators can be calculated with the following equations.

$$IPEI_E = K_1 \cdot \left(\frac{E_{h,av}}{E_{h,av,R}} + K_2 \right);\ IPEI_L = K_1 \cdot \left(\frac{L_{av}}{L_{av,R}} + K_2 \right)$$

where K_1 is a constant equal to 0.476, K_2 a constant equal to 0.524, $E_{h,av}$ is the average horizontal illuminance on the road surface, $E_{h,av,R}$ is the limit value of the illuminance for the corresponding lighting class, L_{av} is the average luminance on the road surface and $L_{av,R}$ is the limit value of the luminance for the corresponding lighting class. The values of $E_{h,av,R}$ and $L_{av,R}$ are given in the local regulation of Emilia Romagna Region [55].

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