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Article

Maintenance and Energy Optimization of Lighting Systems for the Improvement of Historic Buildings: A Case Study

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Abstract: Proper lighting is vital to improve, from an artistic point of view, the surface expanse and decorative detailing of architectural heritage buildings considered valuable. When properly lit, monumental buildings can become to onlookers an essential part of the city. Nowadays, for design planners dealing with the improvement of buildings, whose architectural design should be valorized, the real challenge is to combine the lighting artistic requirements with scrupulous economic management in order to limit the energy demand and to respect the environment. For these reasons, this case study examines the lighting of the monumental façade and the cloister of St. Peter in Chains situated in the Faculty of Engineering of Sapienza University of Rome. The present lighting installation, characterized by metal halides, compact fluorescent and halogen lamps, is compared with an alternative scenario presenting LED lamps and scenographic lighting of the monumental façade. Such comparison is based on the evaluation of the lighting levels for different visual tasks and on energy and maintenance issues; the first analysis was performed through the software DIALux Evo 4.0, whereas the second was performed using ecoCALC. This study leads to the conclusion that the lighting levels of the solution presenting LED lamps are better than those of the present solution, and they comply with current standards. Finally, the higher costs of LED lamp installations and the scenographic lighting of the monumental façade are balanced by lower maintenance costs, with a payback period of seven years.

Keywords: lighting simulations; LED; historic buildings; maintenance; economic analysis

1. Introduction

In the past twenty years, the attention paid to the lighting sector has increased [1–4] and, in particular, the attitude towards lighting of outdoor spaces has changed during this time. More attention has been paid to improvement programs for cities and different ways to experience urban areas: the identity of cultural and architectural heritage sites has been promoted in order make cities more pleasant and livable during the night. Nowadays, the number of people performing outdoor activities in the nighttime is higher, and the proper lighting of outdoor spaces is one of the factors that has led to this widespread phenomenon. Proper lighting, besides creating a safer environment, must also enable a spectator to enjoy the atmosphere while revealing shapes and features of the city. Several times it has been underlined how illumination can affect personal sensations [5–7].

Such influence is even more significant when dealing with monuments, which has been more of a focus of study in recent years [8–12]. They represent works of art and architecture and, from an artistic perspective, monuments are now part of the collective consciousness for many reasons (e.g., historical, memorial, *etc*.): they symbolize historical moments describing something that has happened or give form to the emotions of the artist who created them. For these reasons, monuments pay homage to an historical period, an idea or opinion.

However, while referring to monuments and works of art, the analysis and discussion is often limited to museums and exhibition spaces. For example, Iliadis [13] studied the lighting of exhibits in museum showcases and developed a method to optimize the design for a free-standing showcase in the form of a rectangular parallelepiped with a wooden base and glass cover. However, in these spaces the lighting design is determined by the architect and curator who makes decisions regarding lighting while trying to create a balance between vision and preservation [14–16]. Therefore, the experience of the visitor is controlled by those who organized the lighting, usually preferring to give a certain effect from a certain spot, and the visitor does not have any power to change this condition [17]. This is something that does not happen in outdoor spaces: if someone observes and walks around a monument, in an archaeological site or in a historic centre properly illuminated, he/she can appreciate the extraordinary effects and the sensations given by its lighting. From this point of view, Tural and Yener [18] suggested the need for monument lighting, taking it as an essential architectural and outdoor lighting issue, and they evaluated different lighting conditions of the Bilkent University Atatürk Monument. Di Salvo [19] focused on the importance of respecting the authenticity of sites trying to show both their historical and architectural value, and four different sites were taken into consideration in this study: the archaeological crypt of Notre Dame in Paris, La Ciutadella de Roses in Catalonia, the London's Roman amphitheater and the archaeological Park of Selinunte. On the other hand, Cevik *et al.* [20] stressed, through the analysis of Kunduracilar Street in Trabzon (Tuekry), how a lighting installation, able to emphasize the characteristics of historic buildings, can play an important role in renovation-revitalization works in historical city centres.

Such issues, and from a more general point of view, the same lighting, should be evaluated while taking into consideration the energy consumption related to the lighting requirements [21]. According to the US Department of Energy [22], 7% of total energy consumption is due to lighting and this value increases to 18% taking into consideration electric energy only. In Sweden, observing the data provided by the Swedish Energy Agency, lighting consumption represents 23% of the total value [23] whereas in Italy it is 16.4% [24]. This is why several studies have focused their attention on the optimization of lighting systems and on the corresponding energy savings [25–28]. For example, the substitution of outdated lamps with light sources characterized by a specific efficiency of 117 lm/W can achieve energy savings of about 55% [28].

For these reasons, modern technology suggests the use of LED lamps as a solution to these problems [29]. They allow design engineers to reach high performances both aesthetically and in terms of energy consumption. They also present high specific efficiency values and, for what concerns reliability, they guarantee a higher MTTF (Mean Time To Failure, it describes time to failure for non-repairable components like an integrated circuit soldered on a circuit board and it is expressed in hours) [30] than other lamps. Finally, even if LED lamps present higher investment costs, their MTTF values lead them to have lower maintenance costs.

While considering what has been previously said, this paper makes an evaluation of the lighting of a site characterized by a high historic-artistic value: the cloister of St. Peter in Chains (placed inside the Faculty of Engineering of the "Sapienza" University of Rome) and the exterior monumental façade of the same faculty. Currently, the problem is that the façade (which sees the installation of halogen lamps) is poorly lit and its characteristics are not emphasized. However, the implementation of a scenographic lighting of the façade, while keeping in the cloister the present lighting fixtures (metal halides and compact fluorescent lamps) implies an increase of both the total installed power and the energy consumption because of their specific efficiency values. For this reason, a change in the lighting fixtures of the cloister was made, and the façade and two different lighting installations were compared: a pre-renovation and a post-renovation scenario. The first one reproduces the present lighting configuration of the site whereas the second solution is characterized by LED lamps and the implementation of the aforementioned scenographic lighting of the exterior monumental façade. Thanks to the high values of specific efficiency of LED lamps, the second solution presents a total installed power similar to the one of the pre-renovation scenario. Therefore, thanks to an economic analysis, which considers energy and maintenance aspects [31–35], the purpose is to evaluate whether lower maintenance costs, hence lower operation costs of LED lamps, can balance out their higher installation costs and determine the payback period. While comparing both scenarios, it was also taken into consideration the lighting levels regarding different visual tasks. For this kind of evaluation, the software DIALux Evo 4.0 was used, while for the economic analysis the software ecoCALC was used.

2. The Case Study

The Faculty of Engineering of the "Sapienza" University of Rome is placed in what used to be the monastery of the church of St. Peter in Chains. Its high historical and artistic value is determined by the presence of a Renaissance cloister by Giuliano da Sangallo (Figure 1A) and a monumental façade at the entrance designed in 1916 by Giovanni Battista Milani (Figure 1B).

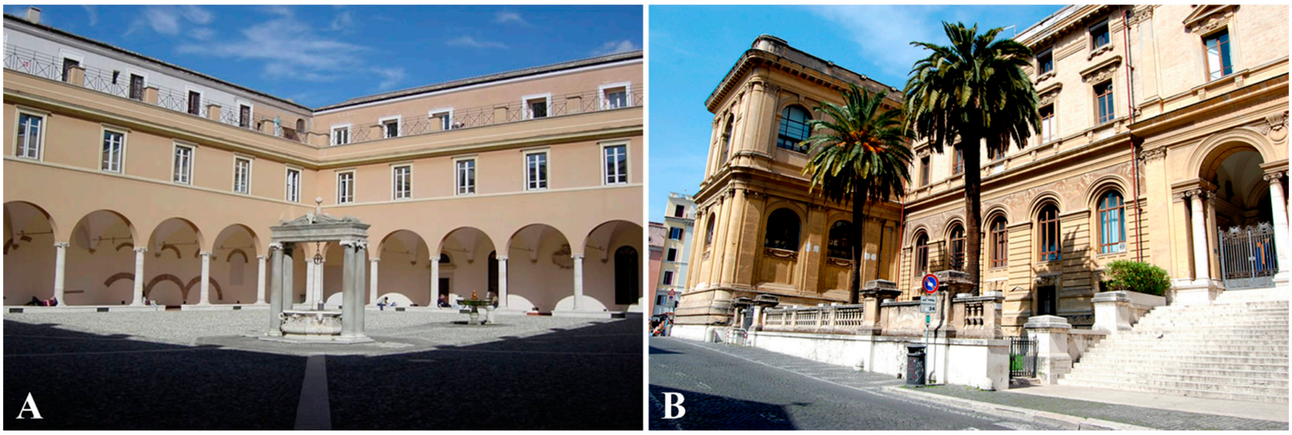

Figure 1. Cloister (**A**) and exterior facade at the entrance (**B**) of the Faculty of Engineering of the "Sapienza" University of Rome.

For what concerns the cloister (Figures 1A and 2), the ground floor is characterized by a rectangular portico whose sides present seven or eight arches supported by columns. The facades on the top of the columns delimiting the portico have, according to the side considered, seven or eight rectangular windows characterizing the first floor; the second floor presents a terrace with the same surface of the portico and placed (in terms of space) right above it. In the middle of the yard there is then an octagonal well thought to be a work by Simone Mosca. The upper part of the well is characterized by a tripod formed by two pairs of columns supporting an architrave thought to be a work by Michelangelo Buonarroti. Moreover, the yard, made of Lombard cobblestones, presents a fountain and an orange tree whereas the portico flooring is made of ceramic tiles. The total area of the cloister is about 1800 m^2, where 1152 m^2 form the yard and 648 m^2 the portico. Figure 2 shows a 3D-model of the cloister and, through the use of letters as ID, all the different surfaces were identified; for each of them Table 1 reports the materials and the corresponding reflection coefficients.

Table 1. Material and reflection coefficients of the surfaces characterizing the cloister.

	Surface Examined	ID	Material of the Surface Examined	Reflection Coefficient [%]
Cloister	Portico flooring	a	Red ceramic tiles	12
	Terrace flooring	b	Red ceramic tiles	12
	Vertical walls of the portico	c	White painted lime plaster	82
	Yard facades	d	Orange painted lime plaster	29
	Columns and bases	e	Marble	71
	Yard surface	f	Cobblestone	28

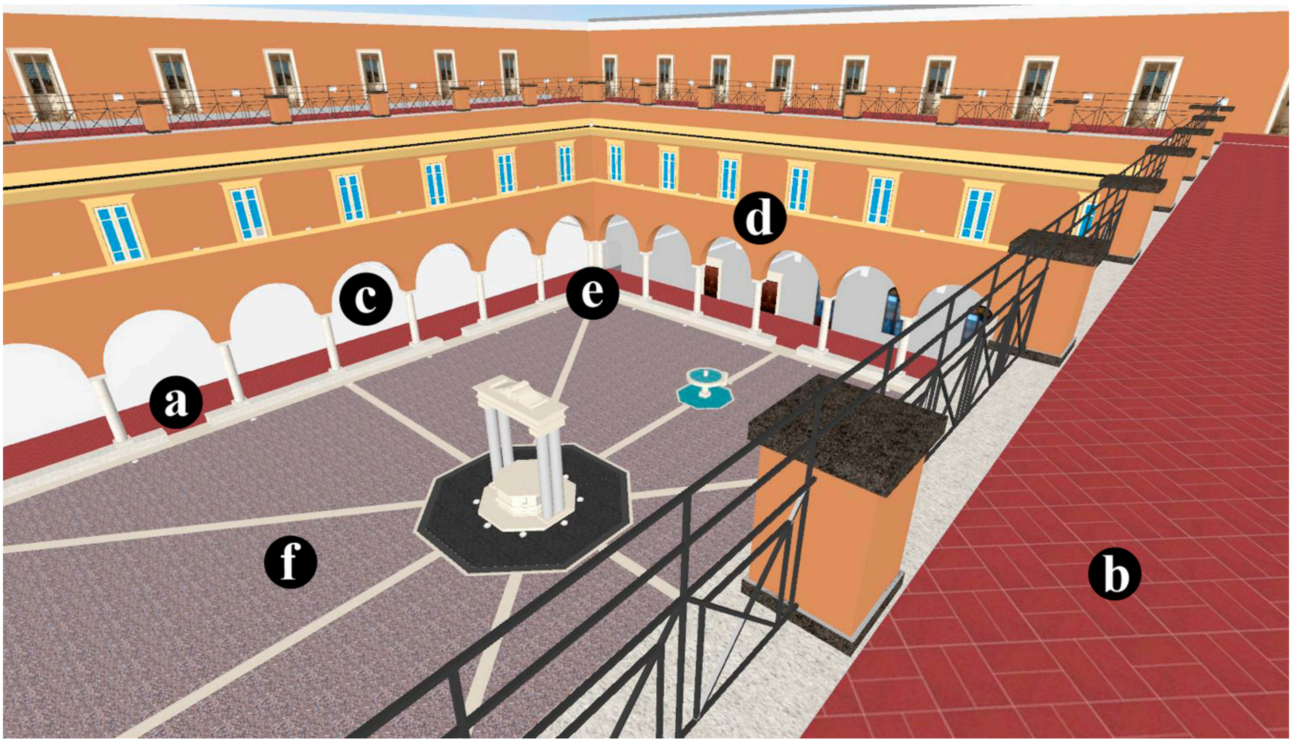

Figure 2. 3D-model of the cloister and identification of the various surfaces.

On the other hand, the main facade of the faculty is on via Eudossiana (Figures 1B and 3), its length is 80 m with a height of 21 m. On the top, there is a banister and it is divided in half by a cornice placed at 11.5 m from the ground. Above and under this cornice there are two types of windows and in the middle three arches representing the entrance. These arches, each supported by two columns, are placed on a staircase formed by 19 steps and both sides are delimited by a banister. The building is then characterized, in addition to the central structure, by two wings. Each wing presents two sides: one towards the entrance overlooking an internal area of 280 m^2 with two high palm trees while the other side overlooks via Eudossiana. The internal side of the left wing presents two types of windows divided by a cornice at 11.5 m from the ground; on the internal side of the right wing, the same cornice separates three orders of windows: two of them are on the lower part whereas the other is on the upper part. Instead, on the sides of the wings overlooking via Eudossiana there are just two arched windows, one on the upper part and the other on the lower part, divided even in this case by a cornice placed at 11.5 m from the ground.

In the wings of the structure, there are then fake columns, used to separate each window from one another. Finally, the areas in front of the internal sides of the wings are delimited, on two sides, by the same building, whereas the other two are delimited by steps and an enclosure constituted by small columns. The case study also considers the entrance hall placed at the end of the entrance staircase. As for the cloister, Figure 3 shows the surfaces of the structure and for each of them Table 2 reports the materials and the corresponding reflection coefficients.

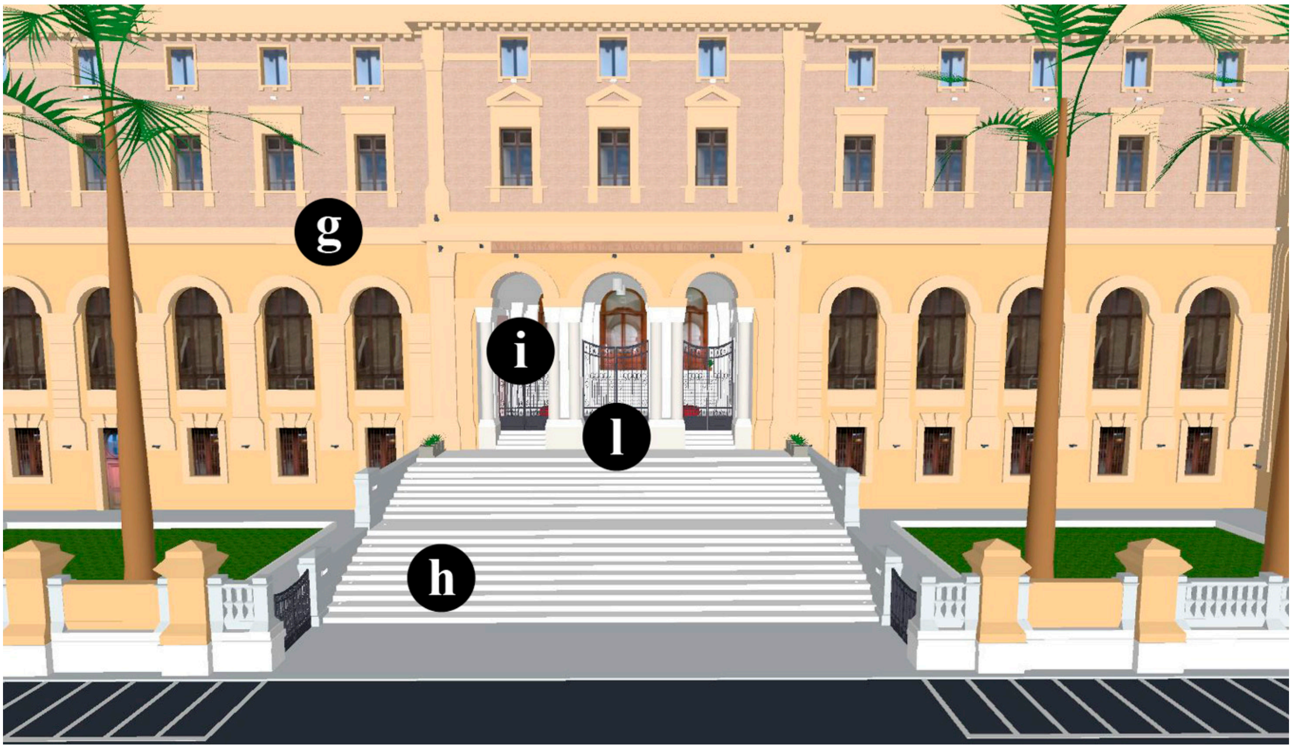

Figure 3. 3D-model of the façade and the entrance hall and identification of the various surfaces.

Table 2. Material and reflection coefficients of the surfaces characterizing the façade and the entrance hall.

Surface Examined		ID	Material of the Surface Examined	Reflection Coefficient [%]
Monumental facade at the entrance	Facade	g	Bricks	42
			Light orange painted lime plaster	46
	Staircase	h	Marble	71
Entrance hall	Vertical walls	i	White painted lime plaster	82
	Floor	l	Marble	71

To complete the characterization of the case study, the lighting configurations of both scenarios examined are then described.

Therefore, with reference to the pre-renovation scenario, Table 3 provides information about the devices currently installed to light the cloister, the façade and the entrance hall: it reports the number of devices, the power of each device and the corresponding total power, correlated colour temperature (CCT) and colour rendering index (CRI).

The lighting fixtures reported in Table 3 include recess spotlights for the portico, the entrance hall and the yard, whereas they are wall devices for the terrace and exterior lights for the façade. The total power for the pre-renovation scenario is 4735.2 W.

On the other hand, Table 4 reports some information concerning the lighting configuration of the post-renovation scenario. As previously said, it assumes a substitution of the present lighting fixtures with LED lamps and, due to the scenographic lighting of the monumental façade, it presents a total power of 5128 W.

Table 3. Current lighting configuration (pre-renovation scenario).

		Type of Lamps	Number of Devices	Power of each Device [W]	Total Power [W]	CCT [K]	CRI
Cloister	Portico	Metal halides	34	24	816	2800	100
	Yard	Metal halides	30	24	720	2800	100
		Compact fluorescent lamps	4	21	84	2700	85
	Terrace	Compact fluorescent lamps	38	20	760	2700	85
Monumental facade at the entrance		Halogen lamps	8	259.4	2,075.2	2900	100
Entrance hall		Halogen lamps	8	35	280	2900	100

Table 4. Suggested lighting configuration (post-renovation scenario).

		Type of Lamps	Number of Devices	Power of each Device [W]	Total Power [W]	CCT [K]	CRI
Cloister	Portico	LED	68	8	544	4000	84
	Yard	LED	34	16	544	2800	84
	Terrace	LED	38	10	380	2800	83
Monumental façade at the entrance		LED Type 1	26	3.5	3000	4000	75
		LED Type 2	28	44		4000	80
		LED Type 3	28	27.5		6000	80
		LED Type 4	13	21		4000	80
		LED Type 5	3	22		4500	80
		LED Type 6	4	35		4000	80
		LED Type 7	2	22		4000	75
		LED Type 8	4	5		4000	70
		LED Type 9	6	17.7		5500	70
		LED Type 10	3	5.1		6000	75
		LED Type 11	2	121		5000	70
Entrance hall		LED	4	165	660	3000	84

3. Material and Methods

3.1. Methodology

In order to give the façade a proper lighting installation which optimizes energy and maintenance costs, hence with total operation costs lower than those characterizing the pre-renovation scenario, a procedure constituting different steps was adopted:

i. The preliminary phase identified:
   - the dimensions of the whole structure through measurements carried out with a laser distancemeter;
   - the materials forming the surfaces of the cloister and the façade;
   - the lighting fixtures characterizing the pre-renovation scenario;
   - the lighting values present in the site and sampled through a luxmeter.

ii. During the second phase, a 3D-model of the cloister and the façade was realized through the software DIALux Evo 4.0 [36].
iii. During the third phase, the lighting installation of the pre-renovation scenario was implemented in the 3D-model.
iv. Validation of the simulation model through a comparison between the experimentally measured lighting values and those provided as output by DIALux Evo 4.0 [36].
v. Simulation of the lighting installation of the post-renovation scenario in the validated model.
vi. Comparison of the lighting values between the pre-renovation scenario and the post-renovation scenario.
vii. Iterative procedure between point vi and v to decide where to locate the lighting fixtures to ensure lighting levels comply with the standards and present values which are not lower than those of the pre-renovation scenario.
viii. Economic analysis of energy consumptions and maintenance costs of the lighting installations of the two scenarios.
ix. Iterative procedure between point viii and v to have a lighting installation which was economically more advantageous (installation costs of the new lighting fixtures + total energy and maintenance costs during the service life of the lighting installation of the post-renovation scenario ≤ total energy and maintenance costs during the service life of the lighting system of the pre-renovation scenario).

The iterative procedure described in the steps vii and ix led to the lighting installation of the post-renovation scenario reported in Table 4.

3.2. Software

In order to carry out this study, two different software systems were used: DIALux Evo 4.0 [36] for the lighting analysis, and ecoCALC [37] for the economic analysis.

DIALux Evo 4.0 allows to plan both indoor and outdoor spaces and for the calculation it uses the radiosity method [38,39]. It is a computational model based on the principle of conservation of energy and the idea that all the light projected on a surface which is not absorbed is remitted by this surface. In addition to this, a surface can also be luminous in itself.

The model can also evaluate the light coming from the sky or one of its sections. Through the radiosity method, an equation for each surface is solved, providing a set of equations whose solutions represent the brightness of every surface.

Once the geometry is created, the model will divide it into surfaces and patches: such division is necessary because a surface can have different luminance values. The standard EN 12464-2 [40] and other regulations provide parameters for the construction of the mesh. The maximum patch size value (value that cannot be exceeded) is provided by these parameters and, in order to satisfy them, the DIALux software uses the following relationship:

$$p = 0.2 \cdot 5^{log_{10} d} \tag{1}$$

where d represents the maximum dimension of a surface and p the maximum patch size. However, it is an adaptive mesh: when the lighting of a surface presents significant changes, the surface will be divided into smaller cells. The ratio between time of calculation and the grid cell size is then not linear but rather exponential since the surfaces can interact with one another.

For what concerns the computational method, it is based on a hierarchical process using a link structure estimating which portions of the surface exchange light [41]. The light exchange occurs only when the link structure is created. The portions of the surface exchanging light are then redetermined and the calculation of the light exchange is performed again: this process is repeated and the results obtained will approximate the real light conditions. Finally, this link structure can be considered a compact representation of the form factor matrix.

On the other hand, the software ecoCALC was used for the economic analysis. This software is able to evaluate the payback period of a solution while comparing it to a basic case (in this study it is the pre-renovation scenario) according to the energy and maintenance savings produced through an investment in alternative technologies. It takes into consideration the basic concepts of the economic analysis of financial planning [42] and, in order to perform the calculation, the software requires the following information: the price of electric energy; the number, luminous flux, electric power and prices of the lighting fixtures chosen to be compared in the different scenarios; hourly costs of maintenance expenses of the lighting system and the spaces examined; the time intervals between the maintenance intervention and realization periods; the dimensions of the space examined; financial data such as interest and inflation rates.

4. Validation of the Model

Once the reproduction of the cloister through the software DIALux Evo 4.0 is done, the next step is the lighting simulation of the pre-renovation scenario to validate the model against the existing lighting installation. The lighting values determined by this simulation were compared with those measured experimentally on the field [43] by examining the surface of the portico where the standards require a lighting of 5 lux [40]. This is the reason why 16 measuring points were set on the surface considered (Figure 4).

To validate the model, we chose to study this surface because of its position in an enclosed environment. For this reason, lighting values are determined by the contribution of the lighting devices installed (the software is able to reproduce them) and they are not affected by external factors.

To perform the experimental measurements, a luxometer whose metrological properties are reported in Table 5 was then used.

Table 5. Metrological properties of the luxometer.

	Measurement range	Accuracy
Luxometer	0.01 ÷ 99,900 lux	±2% of recording

Figure 5 compares the values determined by the simulation performed through DIALux and those measured on the field for each measuring point.

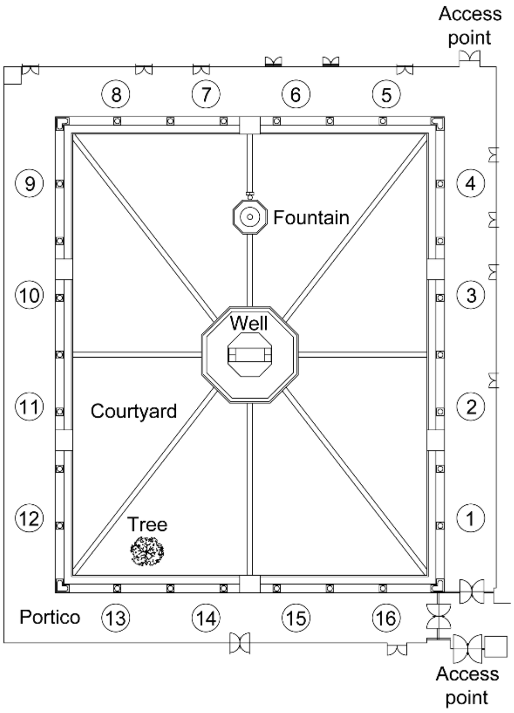

Figure 4. Disposition of the 16 measuring points on the surface of the portico for the experimental measurements.

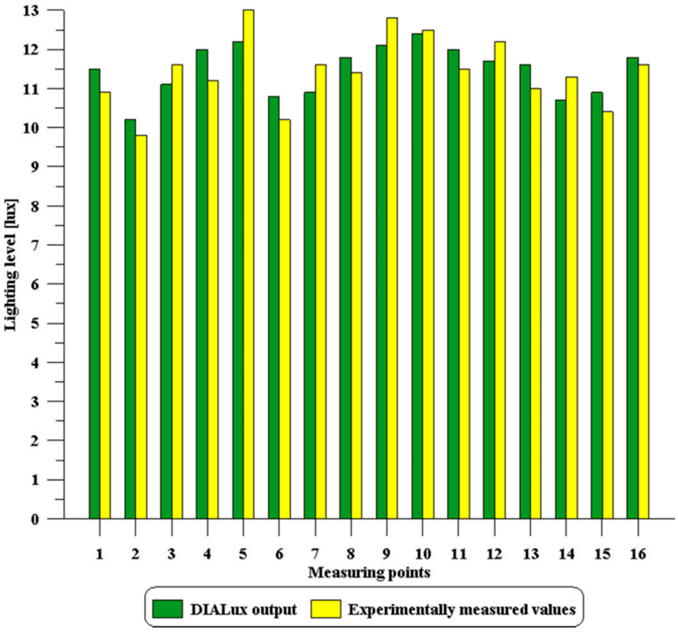

Figure 5. Comparison between the values determined by the simulation performed through DIALux and those measured experimentally on the field.

It can be noted, while examining Figure 3, how there is a satisfying correspondence between estimated and observed data. Such correspondence is also confirmed by the value provided by a numerical index: the mean absolute error MAE [44]. It is defined as follows in Equation (2):

$$MAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n} \tag{2}$$

The analysis of this index led to satisfying results and the resulting value was 0.53 lux. The highest absolute error was found in measuring points 4 and 5 and was 0.8; the minimum absolute error was 0.1 characterizing point 10. As a proof of the validity of the model reproduced, it is possible to note how the absolute errors have values always less than 10%.

5. Lighting Results

Through the DIALux software, it was possible to conduct an evaluation of the lighting results determined by the considered solutions. The pre-renovation scenario is characterized by metal halide lamps, compact fluorescent lamps and halogen lamps. On the other hand, the post-renovation scenario uses LED lamps, and thanks to its implementation, the possibility of redirecting the energy and maintenance savings made by the scenographic lighting of the external façade to the entrance can be explored. It is also important to understand whether the post-renovation scenario is able to provide lighting results that can observe, where necessary, the standards.

This is the reason why the results provided by the simulations for each scenario were evaluated by taking into consideration the same visual tasks and hence the same calculation surfaces. Table 6 reports then the results for every calculation surface for what concerns the average lighting level and the coefficient of uniformity:

Table 6. Comparison concerning the calculation surfaces between both scenarios.

Surface Examined		**$E_{AVERAGE}$ [lux]**			**$E_{MIN}/E_{AVERAGE}$**	
		Desired [40,45]	**Pre-Renovation Scenario**	**Post-Renovation Scenario**	**Pre-Renovation Scenario**	**Post-Renovation Scenario**
Cloister	Portico	5	12	24	0.804	0.911
	Terrace	5	6	9	0.718	0.739
Entrance hall	Internal steps	5	28	196	0.741	0.765
	Table 1	200	40	216	0.353	0.738
	Table 2	200	42	227	0.356	0.744
	Transit zone	5	30	188	0.451	0.718
Monumental facade at the entrance	Staircase	5	9	24	0.561	0.648

While examining Table 6, it is possible to note how the post-renovation scenario provides better lighting conditions on each surface considered. Such an improvement is more significant for the entrance hall and its entrance steps. The surfaces of these spaces, regarded as an essential part of the façade, are among those sections that must be valorized. The higher lighting level and uniformity coefficient detailed in both scenarios are therefore important. As a matter of fact, they tend to be used during expositions and promotional events. An improvement, even if less evident, can be detected for the portico and terrace, which are the surfaces of the cloister that can be considered transit zones.

For what concerns the comparison between estimated and desired lighting values, it can be noted how in the post-renovation scenario the results obtained for each surface are satisfying, contrary to the pre-renovation scenario where the results were revealed to be insufficient as detailed in the Table 6.

In the lighting of the cloister and the façade at the entrance (post-renovation scenario), aesthetic factors were also taken into consideration. So, Figure 6A and B) shows the ray tracing of the cloister.

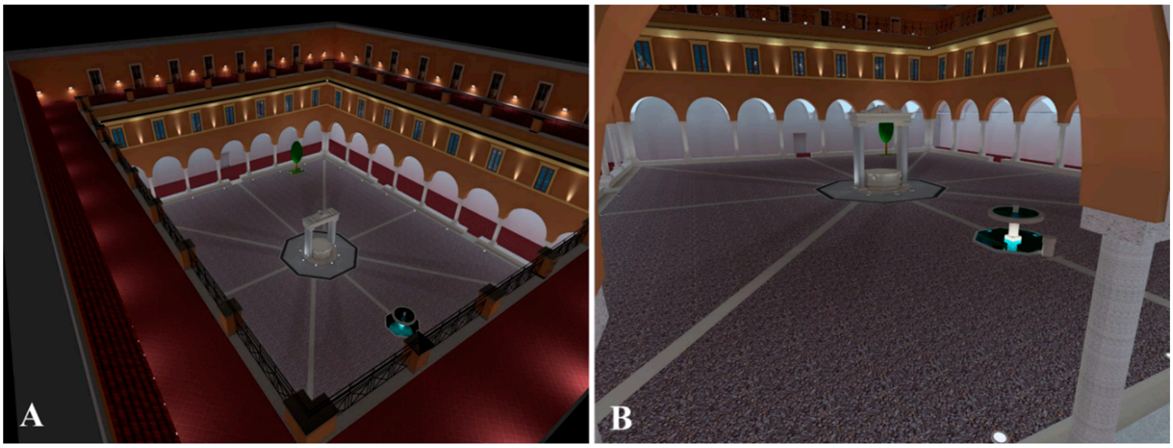

Figure 6. Ray tracing of the cloister in the post-renovation scenario (**A**) view from above; (**B**) view from Portico.

The lighting devices characterizing the façade (Figure 7) were then placed to give prominence to every single element as the columns or friezes; the entrance and other important parts of the building were highlighted as well. Since the building must be observed at a short distance, the number of low power lighting fixtures was increased with respect to the pre-renovation scenario. The small size of the lighting fixtures ensures good optical conditions as does directly installing the lights on the façade. Moreover, this method determines a better flexibility and shadows impression with a higher level of the final lighting effect. To use this type of lighting system, narrow beam spotlights, accentuating the joint of the façade in the vertical direction, were used. Due to their installation position, at a short distance from the façade, the result was a marked grazing light.

Figure 7. Ray tracing of the façade in the pre-renovation (**A**) and post-renovation scenario (**B**).

Finally, these choices ensured, for the post-renovation scenario (Figure 7B), an improvement in the aesthetic qualities of the building with respect to the pre-renovation scenario (Figure 7A).

6. Comparison Based on Energy and Maintenance Factors

From a general point of view, when dealing with buildings, the energy [46–51] and maintenance [52] analyses are extremely important. For this reason, after discussing all these improvements in lighting due to the development of the post-renovation scenario, the comparison between the two scenarios is performed using the commercial software ecoCALC [37]. The comparison did not consider just energy savings achieved by the use of the new LED technology, but it also carried out an examination of the corrective maintenance costs.

Costs are then calculated in Euros, and Table 7 reports some economic and financial parameters that are useful for the estimation and are valid in Italy [53].

Table 7. Values of some economic and financial parameters.

Economic and Financial Parameters	
Price of the electric energy	0.063 €/kWh
Maintenance payment per hour	25.6 €/h
Maintenance cost for the repainting of the building	10 €/m^2
Maintenance cycle for the building painting	25 years
Inflation rate due to the economic calculation	1.80% year
Interest rate of the capital	2.50% year

While comparing the scenarios, it is necessary to consider that in this case LED devices are supposed to function for 50,000 h (assuming an optimal operating temperature) and, according to the annual operating hours of the devices installed on the structure, it is assumed they have a service life of 26 years.

However, it should not be forgotten that maintenance costs of the LED system characterizing the post-renovation scenario are lower than those of the pre-renovation scenario. In fact, metal halides lamps, compact fluorescent lamps and halogen lamps require a more frequent substitution than LED lamps (Table 8).

Table 8. Lifespan and cost of light sources used in both scenarios.

		Pre-Renovation Scenario			**Post-Renovation Scenario**		
		Type of lamps	**Lifespan [h]**	**Cost [€]**	**Type of lamps**	**Lifespan [h]**	**Cost [€]**
Cloister	Portico	Metal halides	6000	35.00	LED	50,000	119.62
	Yard	Metal halides	6000	35.00	LED	50,000	60.00
		Compact fluorescent lamps	8000	51.00			
	Terrace	Compact fluorescent lamps	8000	36.00	LED	50,000	40.30
Monumental façade at the entrance		Halogen lamps	2000	430.00	LED Type 1	50,000	58.37
					LED Type 2		294.38
					LED Type 3		68.10
					LED Type 4		154.33
					LED Type 5		215.30
					LED Type 6		352.00
					LED Type 7		197.25
					LED Type 8		59.04
					LED Type 9		239.21
					LED Type 10		195.33
					LED Type 11		244.24
Entrance hall		Halogen lamps	2000	65.00	LED	50,000	329.25

Table 9 reports then the results from the comparison between the two scenarios.

Table 9. Comparison of the results of the pre-renovation scenario and post-renovation scenario.

	Pre-Renovation Scenario	**Post-Renovation Scenario**
Power installed [W]	4735.2	5128
Average annual total costs (absolute) [€/year]	7749	4823
Average annual energy consumptions [kWh/year]	9506	10,293
Total investment costs [€]	10,387	36,839
Average annual maintenance [€/year]	6272	2292
Average annual operation costs [€/year]	7301	3407

It can be noticed how, due to the number of devices installed to create scenographic lighting on the façade at the entrance, the power installed in the post-renovation scenario is about 400 W higher than that characterizing the pre-renovation scenario. As a matter of fact, in the pre-renovation scenario, the cloister only has 912 W more power installed than the post-renovation scenario, despite the better lighting levels reported.

The power installed affects the average annual energy consumption: the results showing the LED devices consumed 10,293 kWh/year, while in the pre-renovation scenario 9506 kWh/year was used.

Installation costs also represent a advantage for the current solution characterized by metal halides lamps, compact fluorescent lamps and halogen lamps. The higher cost of LED devices leads to a value of 36,839 €, which is 26,000 € more than the pre-renovation scenario.

For a complete evaluation of both scenarios, the average annual maintenance and operation costs must be taken into consideration. From this perspective, the service life of LED lamps implies less frequent substitutions than the lamps constituting the pre-renovation scenario, and this affects the average annual maintenance costs (the post-renovation scenario saves 4000 € with respect to the post-renovation scenario). In turn, this aspect affects the average annual operation costs with a value of 4000 € less than the post-renovation scenario.

Keeping in mind what has been previously said, the general trend of the total costs of the solutions can be observed in Figure 8. Finally, it is possible to note how, even if the investment costs are higher, a lower value of maintenance costs of LED devices makes the post-renovation scenario more advantageous after seven years from the device installation.

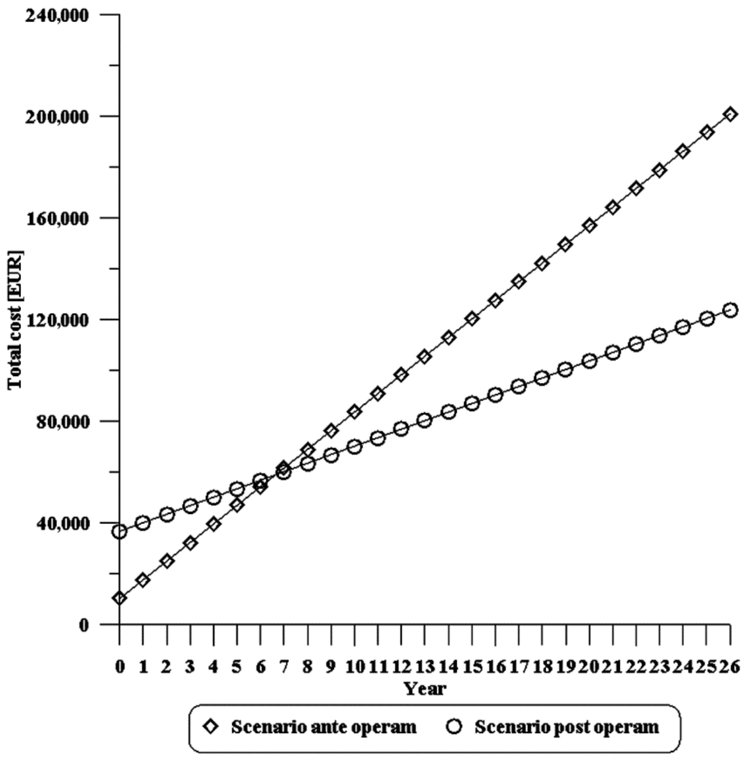

Figure 8. General trend of the total costs for both solutions.

7. Conclusions

This paper, while taking as a case study the cloister and the monumental façade at the entrance of the Faculty of Engineering of the "Sapienza" University of Rome, examines the possibility to substitute the current lighting fixtures with LED lamps and realize a scenographic lighting of the facade. This is the reason why the site examined was reproduced through the DIALux software and the model was validated against the existing lighting installation through a series of experimental measurements in the field. Then, two different scenarios were implemented: a pre-renovation scenario, reproducing the present lighting configuration characterized by the installation of metal halides lamps, compact fluorescent lamps and halogen lamps and a post-renovation scenario, characterized by the installation of LED devices. For what concerns the power installed, the pre-renovation scenario has a capacity of 4735 W while the post-renovation scenario has a capacity of 5128 W. This increase is due to the scenographic lighting of the façade. In fact, in the cloister only, 912 W more power capacity was found in the pre-renovation scenario as compared to the post-renovation scenario.

The next step was to examine the lighting results, and an improvement in the luminance levels on every surface in the scenario with LED devices was reported; uniformity coefficients were improved as well.

The final analysis was an economic evaluation from an energy and maintenance perspective to examine the feasibility of the post-renovation solution. Installation costs of LED lamps were higher. However, as LED lamps present lower maintenance costs and hence operation costs as well, a payback period of seven years was determined for this solution.

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Author Contributions

The study was designed by Ferdinando Salata, Iacopo Golasi, Franco Gugliermetti and Andrea de Lieto Vollaro. Giacomo Falanga and Marco Allegri carried out the numerical simulations. Emanuele de Lieto Vollaro and Fabio Nardecchia retrieved the data from yearbooks and professional websites and reviewed the literature related to the research. The results were then analysed by Ferdinando Salata, Iacopo Golasi and Emanuele de Lieto Vollaro. Experimental measurements on the field were carried out by Francesca Pagliaro. Model design and English corrections were undertaken by Francesca Pagliaro and Fabio Nardecchia. Finally, Franco Gugliermetti and Andrea de Lieto Vollaro, the full professors of the research group, supervised the work related to the paper and the execution of its various phases.

Conflicts of Interest

The authors declare no conflicts of interest.

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