

Article

A Method for Sustainable Lighting, Preventive Conservation, Energy Design and Technology—Lighting a Historical Church Converted into a University Library

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Abstract: Many ancient libraries in Italy are housed in historical buildings, only a few in former churches and monasteries. Newly built libraries mostly comply with the requirements of sustainability, energy saving and renewable energy use, but this does not occur for existing ones, especially when they belong to the historical cultural heritage. Historical library buildings have good mass and thermal inertia but often have inadequate windows with low light transmission value. Lighting systems are often without control and thus cause poor lighting conditions. Our present research concerns the energy sustainability assessment of retrofit operations for lighting in an existing historical university library, focusing on lighting quality, adequate lighting conditions for visual tasks, vision ergonomics and well-being, and guaranteeing the preventive conservation and protection of heritage books. This case study is very particular, because it concerns a Florentine historical monastery which is now a university library. Our proposed method introduces an optimal toolset for lighting design solutions with the aim of sustainability. The library indoor space was procedurally decomposed into illumination volumes according to different occupant activities and visual tasks and different use areas. This method is extensible to all similar cultural heritage case, but also existing old buildings and current designs.

Keywords: quality lighting; vision and perception; historical library; cultural heritage; light experimental method; sustainable lighting; LED

1. Introduction

An above average number of buildings in Italy are of historical value. As a consequence, they are protected and under the constraints of the Italian Heritage Protection Department (known also as Superintendence). When historical buildings are adapted to a different use from the original one, energy solutions for renovation and refurbishment are just as complex as the maintenance of connected indoor microclimatic, thermo-hygrometric, air quality and lighting conditions, especially in the context of the preservation of their historical value, authenticity and integrity [1–6]. At present, there are very few examples of transformation and/or retrofitting of ancient churches of historical and cultural value into university libraries [3,6]. More often, there are design solutions of recovery and/or retrofitting of historical churches as bookstores or shops selling several commercial products.

Today, libraries are conceived and designed as spaces that are more virtual than physical, whether they are part of recovery and retrofitting interventions or new projects: their use, reading and research practices have been transformed and, at the same time, almost all the users have replaced notebooks with laptops, occupying a larger reading station than in the past; while at the PC station, it is also possible to consult a wide variety of texts necessary for study and research. Nowadays, libraries are also an integrated service system.

Of all the libraries in Italy, approximately 50% are subjected to certain limits and over 90% are grade listed [7–9]. Most of them were built prior to 1930. Almost all of them are totally inefficient from energy and environmental points of view [7–9]. Several European programs have highlighted and aimed at integrating the recommendations of the Efficiency Performance Building Directives, EPBD and EPBD2 [10,11], European Committee for Standardization (French: Comité Européen de Normalisation, CEN [12]), then of CEN TC 346 [13] and of the EnerPHit Certified Retrofit (PHI) in historic buildings [14]. The guidelines of the Ministry of Cultural Heritage and Activities (in Italian: Ministero per i Beni e le Attività Culturali, MiBAC) on the energy efficiency of the historical heritage are very important and decisive [15]. There are significant examples of recent European projects in the field of the redevelopment of historic buildings, which were designed and financed for the application of the aforementioned directives, such as the 2009 European project “New energy for old buildings: measures to integrate RES & RUE in historic buildings” (New4old), and good practices for the integration of energy saving and renewable energy production strategies for historic buildings developed in New4Old, 2009 [16].

Appreciable results were obtained under the VII Framework Program with the project “Efficient Energy for EU Cultural Heritage” (3ENCULT project; [17]), concluded in 2011, which concerned the improvement of the energy performance of buildings of historical and architectural interest with public or social functions and which foregrounds how historical buildings are extremely heterogeneous and, from time to time, require specific interventions for protection and improvement of their cultural value.

Another important strategic example in this matter is the pilot project entitled Good Governance in Energy Efficiency (GOVERNEE [18]). It is a European project focusing the use of renewable energy sources in public buildings, with particular reference to buildings of historical value [18].

In the field of refurbishment and retrofitting of historic buildings and the cultural heritage, any lighting project is certainly less invasive, because it does not need wide spaces and a dedicated cavity wall for cables, electrified lines and harnesses, than the one concerning any heating ventilation and air conditioning (HVAC) plant system, and thus it does not require large-scale architectural, structural and functional operations. However, it does have consequences in terms of the rational use of energy (optimal combination of natural and artificial light and their control), energy saving, environmental and light quality sustainability for correct vision and perception, as well as comfort, health and safety. The same is true of the HVAC plant project [19,20]: energy refurbishment and retrofitting of a plant system have major consequences for the rational use of energy, energy saving, efficient solutions for indoor air quality, as well as thermal comfort, health and safety.

However, the sustainability of a lighting design should be conceived in its ability to carry information: light is an information channel that carries signals with informational and cultural content [21].

Our research grew from an ample strategic project of the University of Florence: “Preliminary technical and economic feasibility projects on University of Florence strategic interventions, inside an experimental laboratory”.

The aim of our research is therefore to evaluate how a sustainable lighting project can emphasize the historical, cultural and social value of buildings, as well as allow the recovery of their high historical, artistic and interpretive value. These buildings are today subjected to uses diametrically opposed to those for which they were created and at the same time allow important energy savings and sustainable lighting and quality solutions. Sustainable lighting should be understood as an integrated set of light quality and energy efficiency solutions that in detail means the use of efficient light sources (e.g., lighting emitting diode, LED) integrated with advanced control systems, the light design for a historical/philological extension/refurbishment of the architectural value of the building, for the optimal combination between natural and artificial light, for preventive conservation of the cultural heritage (historical buildings and their previous use), for human visual well-being, quality of perception and vision, visual ergonomics, and satisfaction of the required visual tasks.

Our work started from the assessment of the existing lighting climate of the library located inside a church of high historic-artistic value, in the Engineering Faculty of the University of Florence. The new lighting proposal was based, by means of the study of the light and lighting system in its existing condition, on an experimental methodological approach and lighting simulation aimed at defining sustainable and quality lighting solutions with informative content to return the historical and cultural significance to the environment.

The new lighting proposal is characterized by lower power installation and lower energy consumption because it uses LED lamps of high specific efficiency values and an L50 lifetime (also known as mean time to failure) that describes time to failure for non-repairable components such as an integrated circuit soldered on to a circuit board and expressed in hours. As has been widely shown, even though LED lamps generally have higher investment costs, their L50 lifetime values result in lower maintenance costs [22,23] but also guarantee a significantly lower Lighting Energy Numeric Indicator value (LENI [24,25]).

The research project presented here provides a methodological approach, which could be a useful tool for sustainable lighting design development taking into account preventive conservation, energy design and technology. As has been demonstrated in a piece of fundamental research [26] any kind of project is really unique. The crucial issue, as has also strongly been demonstrated [26], is that the method used, the simulation model, based on raytracing rather than radiosity techniques, the lighting metrics and parameters selected could not only lead to different results but also a lighting design sustainability with insufficient comparable criteria, giving a final score, from a quality and sustainability point of view (e.g., the author refers to the LEED certification [26]) that could be appreciably different [26]. The method proposed here uses an approach based on several, complementary metrics, different but interconnected lighting parameters for defining the luminous environment. In Figure 1, basic steps of the method used are shown by a flow chart. The case study (i.e., a historical church converted into a university library) was used as a pilot and test project in order to check the extensibility, adaptability and real applicability of the proposed methodology to all similar cases.

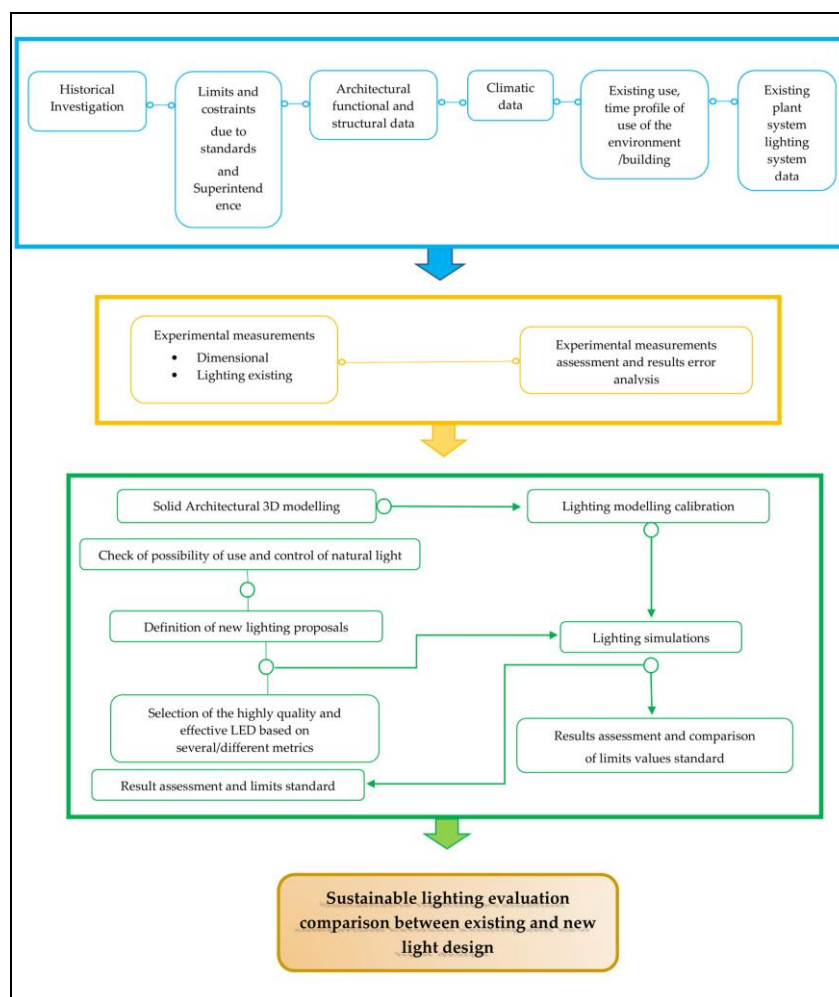


Figure 1. The flow chart of the method used.

2. Materials and Methods

2.1. Experimental Measurements Campaign

An experimental protocol was determined to perform many different sets of illuminance and luminance measurements with a sequential procedure that guarantees the repeatability of the measurement in a short time during the hours of occupation and use of the library. The instruments used and the connected technical characteristics are: Luxmetro CL-200A Konica Minolta, with a silicon photocell of spectral resolution within 6%, measuring range 0.1–99900 lx and precision $\pm 2\% \pm 1$; Konica Minolta CL-S10w colorimeter with a silicon photocell with cosine correction within 3%, measuring range 0.1–99900 lx and accuracy $\pm 2\% \pm 1$; Leica Disto D2 laser class 2 distance meter, range 0.5–60 m, accuracy ± 1.5 mm. The measurement points are those corresponding to the grid defined with reference to [24] and taken on the floor, worktops and walls. In particular, illuminance measurement details (i.e., the positioning of the lux meter from the floor) are as follows: the height from floor for the reading room was taken at 0.000 m, for the apse at 0.80 m, for the working surfaces at 0.72 m and for all the walls at 1.60 m. Basic colorimetric measurements were also performed on significant surfaces and materials.

The lighting measurements were carried out in winter during the hours of opening and use of the library. The existing luminous climate is always the result of the natural and artificial light combination. It should be noted that artificial lighting is never turned off, as evidence of the fact that natural light was not conceived and designed for an (existing) library, but for a liturgical space.

All the data and information concerning the electrical network layouts, wiring, control units, emergency lights, and also the ventilation systems in the real existing condition were collected and analyzed.

2.2. The Case Study

An extensive study was carried out on the historical, architectural and cultural aspects of the building, its different indoor environments and the surrounding context using information from archives of rare printed books and literature sources [27–31]. It was possible to assess the state of preservation, thermo-physical, optical photometric characteristics and possible degradation processes for different materials (mainly wood and paper) and objects, but also to reconstruct the transformation of spaces and functions over time, combining historical research with architectural and geometric surveys. A three-dimensional model of the environment and existing lighting system identification was made using the in-situ architectural relief integrated with geometric specific information provided by the university technical offices.

There is little information on the processes of transformation, retrofitting and refurbishment operations over time of the building and plants, and what there is was difficult to find. The most important results are provided as follows.

A historical search allowed the reconstruction of the main phases of the adaptation and transformation of the church, as well as investigating and reconstructing the most significant philological and historical-cultural aspects. At present, the library is subject to the protection and constraints for conservation and safeguarding issued by the relevant State Authorities and those dealing with the cultural heritage in Tuscany. The building unit, which originally housed the seminary of the Florentine Archdiocese, was owned by the Dell'Accetta family until the 14th century.

Later, it became the object of various financial conflicts of different owners throughout history. The seminar activity continued for a few decades.

The gradual reduction of the number of seminarians in the post-war period resulted in the building being underused. Therefore, in 1980, the Cardinal Giovanni Benelli Archbishop of Florence, sold the seminary to the University of Florence and it became the Engineering Faculty (Figure 2) and the chapel became the faculty library [27–31]. Figure 3 shows Villa Cristina from the Alinari Archives: the historical photo of the minor seminary chapel. The library room consists of an apse of the ancient church, 10.93 m in length, 12.43 m in width and 9.82 m in height. A stone staircase links the apse to a reading room, 22.93 m in length, 12.43 m in width and 10.62 m in height.



Figure 2. Photo of the former minor seminary chapel, that is today a university library.

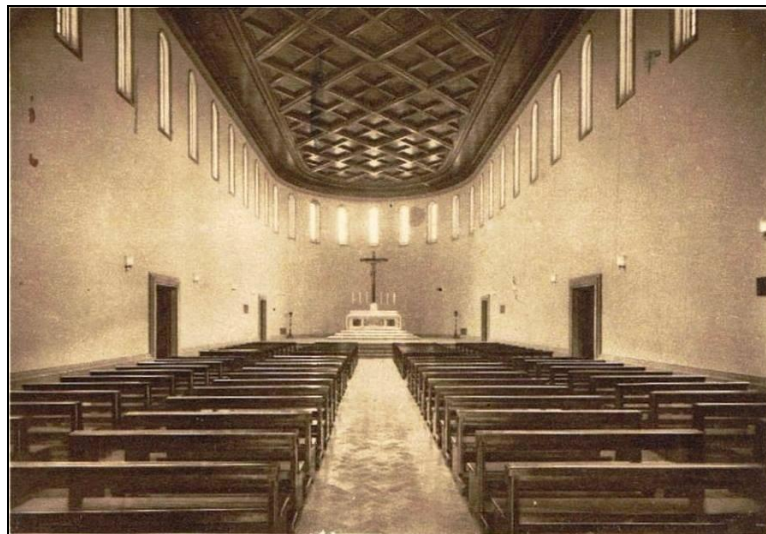


Figure 3. Photo—historical documentation—a view of the minor seminary chapel. Alinari Archive, currently Santa Marta library.

Natural light only enters from vaulted openings placed in the highest part of the two side walls of the church apse, and creates suggestive effects and almost blades of light and shadow: 29 single-glass windows placed at a height of 7.60 m from the floor and, in particular, eight on the East and eight on the West walls, and 13 on the apse walls. As explained in the previous chapter, a lighting experimental measurement campaign was carried out in winter, combined with a colorimetric one.

In particular, the colorimetric measurement results and the corresponding average illuminance level, performed on significant surfaces and materials, are provided in Table 1.

Table 1. Experimental measurement results: illuminance level and colorimetric coordinates of the different zones/objects—existing state.

Zone	Illuminance E_v (lx)	Colorimetric Coordinates	
		x	y
Shelves apse	39.3	0.4612	0.4151
Blue table	59.9	0.4492	0.4094
White Table	33.4	0.4623	0.4094
Gallery shelves	28.4	0.4472	0.4029
Blue Shelves	22.0	0.3859	0.3754
Floor	18.9	0.4949	0.4002
Grey shelves	22.8	0.4348	0.4153
Chairs	52.6	0.4963	0.4153
Wall desk	17.5	0.4048	0.4278
Black table	13.8	0.4465	0.4047
Front door	28.7	0.3877	0.4251

3. Existing Condition of the Light Climate of the Environment

3.1. Results Analysis

In this section, the experimental measurement results are shown and analyzed. Experimental data error analysis was carried out by means of the standard deviation and chi-squared test: the percentage error on the measured illuminance and luminance measured data is very low and both are always below 10%; the standard deviation for luminance and illuminance measured data is 39.61,

and the mean chi-squared error is 38.74. This fact confirms the validity, accuracy and robustness of the experimental methodological approach developed and the measured data reliability. The luminous climate assessment in existing conditions, by means of the experimental measurement campaign results, shows that during the hours of use of the library and for all the lighting conditions, the environment is very dark. Natural light is always low and non-uniform (because it was considered and designed for a historical church) due to highly variable different sky conditions, that at medium–low latitudes, like that of Florence, includes the high variability even in short periods (often also less than ten minutes). Therefore, the experimental results analysis was performed on the condition of mixing between natural and artificial light. The existing artificial lighting system is described in Table 2. Moreover, the illuminance and luminance value distributions are not uniform, causing several zones of light imbalance, visual discomfort and glare. As a matter of fact, the illuminance values (E) measured, but also the ratios calculated between the illuminance minimum value (E_{\min}) and illuminance mean value (E_{mean}), and between the illuminance minimum value (E_{\min}) and the illuminance maximum value (E_{\max}) on the working planes, never meet the limits suggested [32,33]. In Table 3, the experimental data on illuminance values in the apse zone and reading room are provided for the significant hours of library use (i.e., 10:00; 14:00; 18:00.) during winter. Tables 4 and 5, respectively, give the measured illuminance values on the working planes and the luminance values measured (L) during evening on the main surfaces due to only artificial light. The non-compliance of the standard limit values of the illuminance ratios guarantees neither uniform light distribution in the environment nor low differences of luminance and contrast. In particular, for the duration of the measurement campaign (winter), during early afternoon, in the condition of high solar radiation levels, high illuminance imbalances and significant luminance differences were assessed on the work surfaces and walls (i.e., zones of bookshelves) that cause local discomfort glare phenomena.

Table 2. Technical data on the existing lighting system.

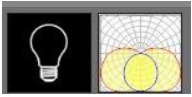
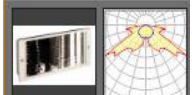

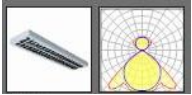
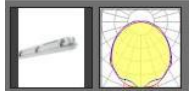

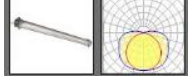
Name	Typology	Image/Luminous Intensity Distribution	Luminous Flux/Power Ratio	Ra	Color Temperature	N. Installed Lamps	Height from Floor
3F LINDA	LED		5200 lm/58 W	80	3000 K	6	3.00 m
Steel LED	LED		2145 lm/58 W	85	5000 K	8	6.51 m
Afrodita	LED		6600 lm/70 W	100	3000 K	6	3.34 m
Canes	Compact fluorescent lamp		1500 lm/36 W	80	4000 K	6	4.50 m
Damp Proof LED	LED		1000 lm/39 W	80	4000 K	4	2.20 m
F30 LED	LED		2000 lm/150 W	84	4000 K	2	6.00 m
Tubular	Compact fluorescent lamp		5000 lm/49 W	85	2000 K	32	6.51 m

Table 3. Experimental values of illuminance (lx) and its significant ratios for typical hours in winter.

	10.00		14.00		18.00	
	Reading Room	Apse	Reading Room	Apse	Reading Room	Apse
E_{min}	6.43	1.41	6.59	1.4	6.05	1.38
E_{max}	245	138	248	141	245	127
E_{mean}	141	79.2	143	80.8	135	72.1
E_{min}/E_{mean}	0.046	0.018	0.046	0.017	0.045	0.019
E_{min}/E_{max}	0.026	0.01	0.027	0.01	0.025	0.011

Table 4. Experimental values of illuminance (lx) obtained from all the measurements carried out in winter.

	Reading Room Table	Reception Table	Apse Table
E_{min}	145	106	43.3
E_{max}	215	238	106
E_{mean}	186	177	79.5

Table 5. Experimental values of luminance (cd/m^2) obtained from all the measurements carried out in winter.

	East Wall	West Wall	Apse Wall
L_{min}	0	0.001	1.65
L_{max}	727	725	36.4
L_{mean}	12	17.2	14.3

3.2. Discussion and Proposal for a New Lighting Design

Any lighting project compared to a heating ventilation air conditioning system project, especially due to retrofitting and refurbishment operations, is less invasive and does not require important changes of the architectural structures and functional parts of the building.

In particular, when it is considered in terms of energy sustainability and quality (rather than quantity) of light and lighting system, it can lead to significant, efficient solutions, based on quality of vision and perception, enhancement of the meaning of space, as well as of the recovery of the historical and philological memory of the environment.

Experimental results obtained were analyzed and compared in connection with possible retrofit operations for lighting the historical library under study, focusing energy sustainability and light quality, quality of vision and adequate lighting conditions for visual tasks, vision ergonomics and well-being and the guarantee of book heritage preventive conservation and protection. The whole building and library are subjected to the restrictions of the Tuscan heritage authorities and this means that building operations are not allowed on windows, architectural structures, roof and ceiling, walls and floors and all kinds of internal features. This fact implies that the efficient use of natural light and its control could not be used for the new lighting design.

Different lighting scenarios were then identified, referring to the historical chapel and the existing use of the environment, restoring its original historical–philological meaning by means of quality and sustainable light. Comparing illuminance and luminance distribution inside the environment due to the existing lighting conditions, different volumes and paths were identified.

The study of light and, in particular, of incoming natural light allowed us to identify different architectural and aesthetic, emotional and perceptive effects, and levels of functional and liturgical luminosity, both for the congregation and the chancel.

According to the natural light trend, it has been possible to identify, reinterpret and recover the historical–philological information and therefore discover the areas and volumes that belong to the history of the church: the narthex, i.e., the short atrium that is as wide as the church, the central nave that very evidently runs up to the choir, the aisles flanking it, barely identifiable due to architectural transformations, the part in which the high altar stands and finally, clearly visible, because it is also marked by the luminous path of the sun, the apse, i.e., the semi-circular portion placed behind the choir and the final part of the whole environment.

These areas now have different uses: reading and study tables are everywhere. In particular, three zones were identified, also taking into account the corresponding illuminance values and photosensitivity classes of the different materials present: the reading room (reading books on open shelves, online consultation, reception); apse room (display of paper material, manuscripts, etc., with important historical value); media room (activities related to software applications use). As a consequence, three lighting scenarios were identified: museum-philological-historical; functional library; exhibition.


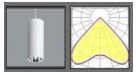
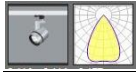

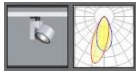
4. New Lighting Design Simulation

4.1. Model Setting and Validation

Starting from the existing lighting condition assessment, a 3D model of the environment was set up and the experimental measurements were used for calibrating and validating the light simulation model. The design solution for new sustainable lighting for the library aimed at the three lighting scenarios described above and was performed with commercial software [34]. The sustainability of the new lighting is mainly due to interventions that are minimally invasive, reversible, easily modifiable and respectful of the constraints of the Italian Heritage Protection Department and Tuscan heritage authorities, for the building and the studied library environment, and also for energy and maintenance cost reduction.

In particular, the existing power supply systems were used for the new LED light sources (Table 6) and all these LEDs were assembled on new differently arranged electrified tracks (longitudinal for the new proposal compared with transversal existing one; Figure 4). The existing LED sources were not reused due to the following limits: the tracking angle was non-orientable, the beam angle was non-variable, and the color rendering index (Ra) was not in accordance with [23,33].

Table 6. Technical data on the lighting system described for the lighting project proposal.

Name	Typology	Control System	Image/Luminous Intensity Distribution	Luminous Flux/Power Ratio	Ra	Rf	Rg	Color Temperature	N. Installed Lamps	Height from Floor
Pen Dlight	LED	DALI		1814 lm/24 W	92	90	100	3039 K	15	2.75 m
Pen Dlight	LED	DALI		1600 lm/18 W	92	90	100	3039 K	8	2.75 m
Parscan	LED COB	DALI		1232 lm/12 W	92	90	99	4000 K	24	6.51 m
Parscan	LED COB	DALI		1232 lm/12 W	92	90	99	4000 K	6	3.50 m
Optec	LED COB	DALI		3513 lm/36 W	92	90	99	4000 K	6	6.51 m

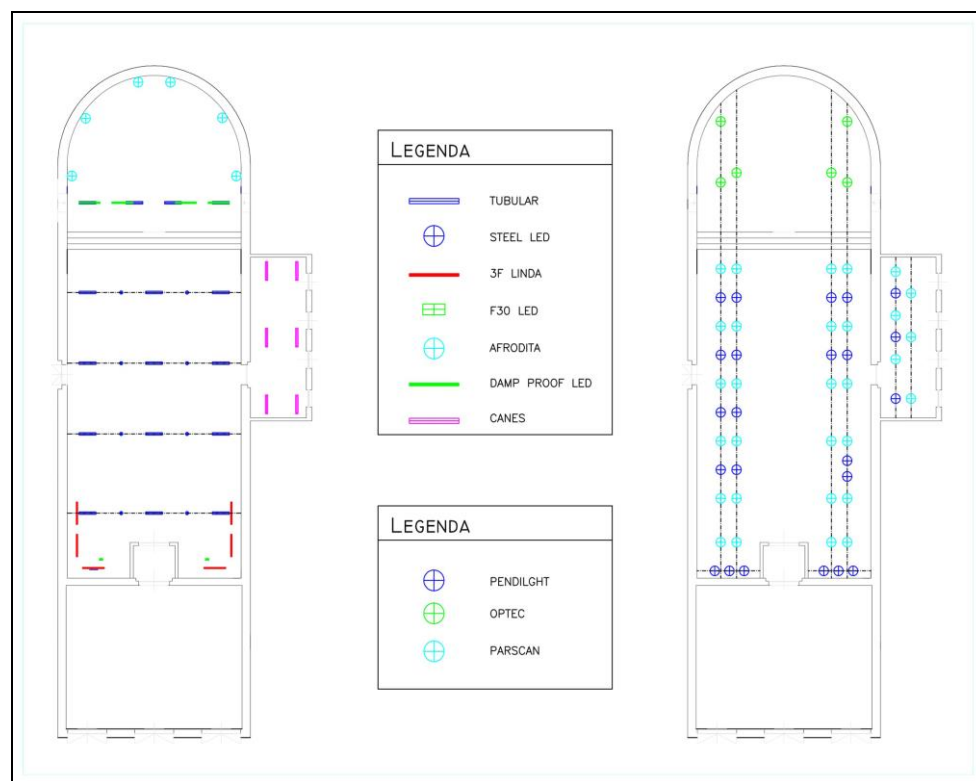


Figure 4. Map scheme of luminaries and electrified tracks arrangement: existing state (left) and new lighting proposal (right).

The Ra values for the existing light sources and those of the new light design can be compared by looking at Tables 2 and 6. The ANSI/IES TM-30-18 [35] suggests metrics based on two indices, the fidelity rendering (Rf) and the gamut rendering (Rg) indices.

Rf, similar to Ra, is an accurate measurement of the average color fidelity with range values from 0 to 100 in comparison with a reference illuminant. The Rf index, does not allow color quality measurements related to perception, in addition to fidelity, nor other effects related to color memory, nor is it a measure of human color preference or the perception of naturalness [26,35].

Therefore, maximizing Rf does not necessarily correspond to the increase of desirability, utility, or any other perceptual attribute of naturalness [26,35].

The Rg index is an index of the gamut: an increase (greater than 100) or a decrease (less than 100) in the average saturation level of the source with respect to the reference illuminant. The Rg index provides information about the relative range of colors that can be produced (with reflection) by a white light source. An Rg score close to 100 indicates that the light source produces colors with saturation levels similar to those of an incandescent bulb (i.e., with 2700 K color temperature) or daylight (i.e., with 5600–6500 K color temperature). For LEDs with good color quality, Rg can typically range between 80 and 120, with higher scores representing higher overall levels of saturation.

The Ra, Rf and Rg index of each LED sources used for the new lighting design were assessed: the results are given in Table 6. The high quality and efficiency of the new LED sources are very clear.

The different lighting scenarios proposed were simulated using the aforementioned LED sources, designing and checking the specific beam and aiming angles, position, and the connected efficient control system with which they are equipped (Table 7). For all the simulations concerning the new lighting design, the same boundary conditions referring to the existing state analysis and simulation were considered: the winter period, variable sky conditions, hours of use of the library and mix between natural and artificial light.

Table 7. Data and work conditions of the control system of LED sources for the lighting project proposal.

Lighting Scenarios	LED Reading Room	LED Media Room	LED Reading Room	LED Apse	LED Cases
Museum-philological-historical	off	off	100% working	100% working	Off
Functional library	100% working	100% working	100% working	off	Off
Exhibition	off	off	60% working	off	switch on passing

In particular, for the exhibition scenario, a Passive Infrared system (PIR) able to detect even limited movement was used for light dimming and control.

4.2. Results and Discussion

The results of the new lighting proposal show that when historical buildings are given over to a different use from the original use, only by means of sustainable lighting design is it possible to recover the cultural and philological value, and original historical and architectural meaning, guaranteeing the use of spaces and performance of different work activities, in compliance with current standards.

Our proposed integrated methodological approach aimed at sustainable lighting design can ensure preventive conservation, efficient energy and LED technology solutions, light quality for vision/perception and act as a crucial part of the process of restoring the historical memory of the (building) environment.

The dimensionless parameter known as Modelling index (M) provided by the standard [36] was evaluated for each proposed lighting scenario, to which the reference scenario defined by the conditions of maximum natural and artificial light (i.e., the precautionary condition of mix between the highest levels of natural and artificial light), the latter with sources working at 100% without dimming and control was compared. M index was computed by reference to the 1.2 m height from the floor for people sitting and 1.6 m height for people standing as required for the average cylindrical illuminance maintained (E_{sc}) evaluation. M describes the balance between diffuse and directed light and then is the ratio of semi-cylindrical illuminance (E_{sc}) to vertical illuminance (E_v) at a point. The M index value, both for the apse zone and from the whole library/reading zone, is always within the limits [35] which is the range 0.8–1.3.

This result demonstrates that the arrangement of the light sources is uniform and the modelling is good (Table 8). As proof of this, the value of the Unified Glare Rating (UGR; [32,33]) was calculated and compared with the suggested limit [33] for all the zones, with particular attention to the areas of visual reading and writing tasks, that perform the functional library scenario and therefore also to the computer workstations. The UGR falls within the recommended values for all the scenarios and related visual tasks.

Table 8. Fundamental illumination design parameters.

	Values	100% Working	Museum-Philological-History	Functional Library	Exhibition
Apse	E_{sc} (1.2 m)	64.5	62.7	39.7	37.2
	E_v (1.2 m)	76.3	74.8	45.2	43.1
	E_{sc} (1.6 m)	71.1	69.2	43.1	40.7
	E_v (1.6 m)	84.3	82.7	49.1	46.9
Reading room	E_{sc} (1.2 m)	59.8	52.6	52.8	40
	E_v (1.2 m)	63.8	56.6	57.4	44.4
	E_{sc} (1.6 m)	62.3	55.5	55.2	42.5
	E_v (1.6 m)	66.6	59.7	60.1	47
Modelling index ($M = E_{sc}/E_v$)	apse (1.2 m)	0.85	0.84	0.88	0.86
	apse (1.6 m)	0.84	0.84	0.88	0.87
	reading room (1.2 m)	0.94	0.93	0.92	0.90
	reading room (1.6 m)	0.94	0.93	0.92	0.90

The visual well-being, light pleasantness and quality of perception were assessed for each lighting scenario connected to its specific use; e.g., the lighting solution for the apse zone (exhibition scenario), guarantees quality of light for the visual task needed for the vision and perception of the exhibited rare books of great historical value, and the illuminance values for preventive conservation and protection. In the apse zone, there are display cabinets for the book heritage, illuminated when visitors approach, for which the 50 lx limit is guaranteed for the protection and preventive conservation of photosensitive material corresponding to the third photosensitivity class (i.e., “High”, [15]) through the light control and dimming, optimally combined with those in the apse, ensuring an environment that is always perceptually uniform.

For all the other scenarios, the proposed lighting solutions guarantee visual comfort and ergonomics, the absence of glare phenomena, as, e.g., the lighting solution for library use (functional library scenario), assessed at 18:00 as a cautionary choice, because of the maximum artificial light sources working condition, provides uniform and homogeneous distribution of illuminance, guaranteeing the limit values due to standards for all the work planes both in the reading room and in the adjacent room (media room; Table 9) and in particular on the vertical plane of all the open shelved books where the mean illuminance level is always in the range 100–150 lx.

Table 9. Illuminance values (lx) for the new lighting proposal.

	Reading Plane	Media Plane	Apse Plane	Reception Plane
E_{min}	436	494	314	444
E_{max}	575	565	666	566
E_{mean}	507	530	513	512

The luminance values, evaluated on the side walls and floor of the reading room and apse zone and compared with the existing condition, are provided in Table 10.

Table 10. Luminance values (cd/m²) for the new lighting proposal.

		East Wall	West Wall	Apse Wall	Reading Room Floor	Apse Floor
Functional library	L_{min}	0.004	0.017	0.63	0	0.02
	L_{max}	31.2	29.1	2.71	5.64	0.75
	L_{mean}	3.35	3.5	1.36	0.77	0.12
Exhibition	L_{min}	0.004	0.002	0.25	0	0.008
	L_{max}	4.03	4.04	2.35	1.17	0.44
	L_{mean}	1.23	1.29	1.00	0.24	0.074
Museum-philological-history	L_{min}	0.005	0.006	0.81	0	0.021
	L_{max}	9.3	10.3	8.87	1.97	0.52
	L_{mean}	3.28	3.55	5.02	0.43	1.54
Existing state	L_{min}	0	0.001	1.65	0.005	0.12
	L_{max}	727	72.5	36.43	14.6	16.3
	L_{mean}	12	17.2	14.30	6.02	4.44

A comparison between the results of Tables 8 and 9 with those obtained by the lighting simulation (Figures 5 and 6), balance and uniformity of luminance and illuminance distribution, is guaranteed for all the lighting solutions and for each scenario.

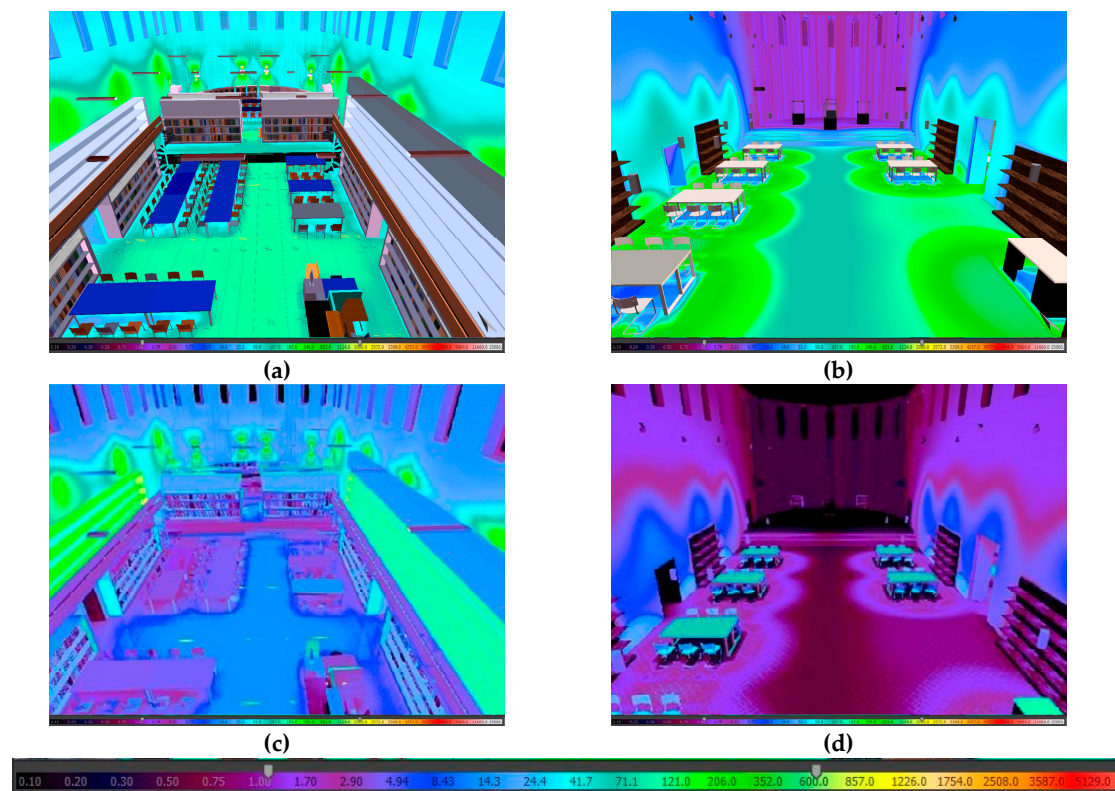


Figure 5. Rendering in false colors of the illuminance (lx) and luminance (cd/m^2) values: (a) illuminance distribution at the existing state; (b) illuminance distribution for functional library, (c) luminance distribution for the existing state, (d) illuminance distribution for functional library.

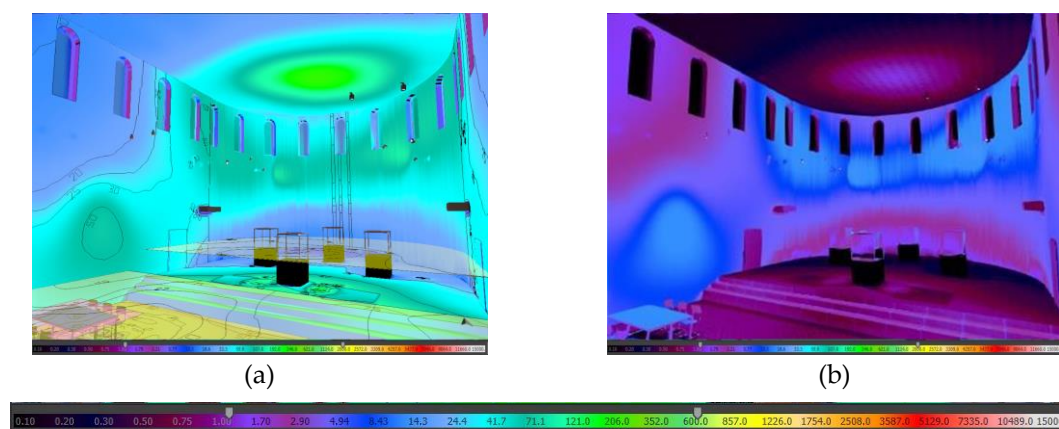


Figure 6. Rendering in false colors of illuminance (lx) and luminance (cd/m^2) values for historical-museum-philological scenario—view from the apse (a) illuminance; (b) luminance.

Simulation results highlight basic differences, from the point of view of treatment and design, between the sustainable and quality light suggested and light at the existing state. In particular, they provide the unmistakable demarcation of the ambient lighting history between the earlier time as a church and today as a library.

The optimal combination between natural and artificial light, as well as the uniform distribution of the illuminance and luminance, for all the three lighting scenarios balanced with the corresponding distributions, but obviously, with different values for the whole environment, can be seen in Figure 7.

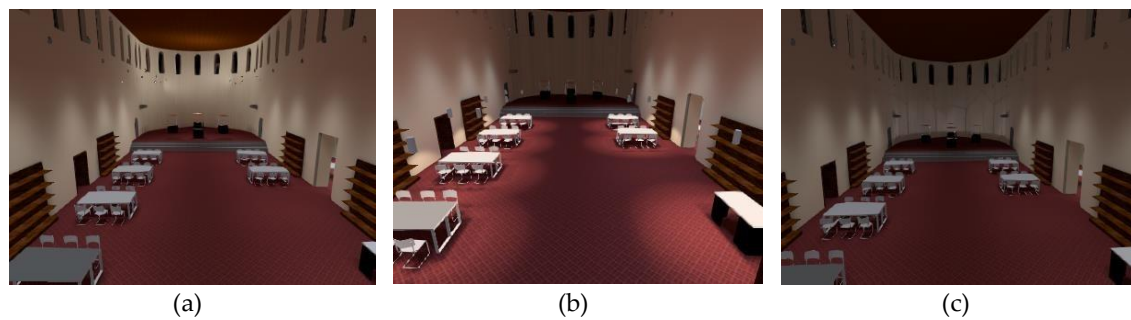


Figure 7. Rendering of different lighting scenarios—view from the entrance: (a) historical-museum-philological, (b) functional library, (c) exhibition

For the energy performance and efficiency assessment of the new lighting proposal, the Lighting Energy Numeric Indicator (LENI), the connected energy consumption and costs were calculated for each lighting scenario and for the existing state.

Table 11 shows these results: it is evident that seeing well with quality light (sustainable lighting for quality vision and perception) has a cost in terms of considerable energy consumption for all the lighting scenarios, although appreciably lower than the existing condition, but at the same time, a LENI value for all the lighting scenarios is always very low.

Table 11. The Lighting Energy Numeric Indicator value (LENI) value, connected energy consumption and costs.

	Existing State	Museum-Philological-History	Functional Library	Exhibition
Consumption (kWh/year)	10300–15100	1950–2750	1400–1850	2750–3900
Costs (£/year)	3093–4528	586–818	413–559	821–1163
LENI (kWh/year/m²)	22–23	4–6	3–4	6–8

A good balance, homogeneity in the distribution and uniformity of the light designed for different scenarios, is evident. To give another example, Figure 8 shows the simulation results by rendering of the different lighting scenarios with a view from the apse.



Figure 8. Rendering of the different lighting scenarios—view from the apse: (a) historical-museum-philological, (b) exhibition.

5. Conclusions

With this research, a methodological approach for sustainable lighting projects was provided.

The proposed method can be a useful support for sustainable lighting and preventive conservation, energy design and technology, based on the qualitative use of light, or for a new design approach that shifts attention to quality (vision and perception) starting from the evaluation of lighting efficacy, energy saving and correct quantity (of light).

The methodology can be applied both to new building projects and buildings/historical environments and/or cultural heritage. For all these cases, knowledge of the luminous climate of the existing state of the environment integrated with knowledge of the history (especially in the interventions of lighting refurbishment) of functional transformations and reorganizations of the intended use of environments is the first crucial step. Consequently, the method, by means of the integration of the experimental campaign of lighting measurements, provides the following basic phases for a sustainable lighting design: the checking of the possibilities of use and control of natural light (combined with the artificial one); the choice and assessment of the quality and efficiency of high quality light sources, by means of analysis and comparison of several interrelated metrics; setting lighting simulation models, calibrated and validated with experimental measurements; the achievement of quality light for correct and comfortable vision and perception, performance of the visual tasks required, visual comfort and the ergonomics of vision, protection and preventive conservation of materials/objects of historical-artistic value. By extension, the proposed method leads to the identification of efficient and effective lighting solutions.

The method particularly aims at preventive conservation, energy design and efficient light technology application. In particular, since it is based on the inclusion and comparison between practical lighting solutions carried out from the historical investigation of the building, of the context and of the different uses of light (natural and artificial) over time, it is possible to identify sustainable lighting solutions. This aims at enhancing space and place, making them usable and recognizable, recovering the historical memory, revisiting, rereading, reinterpreting, reconfiguring and reworking this same space with the “eyes” of scientific knowledge and thought and all lighting technologies and techniques which can be afforded today.

This crucial issue involved the development of experimentation and environmental monitoring carried out considering not only respect of the limit values (the quantity of light), suggested by current standards, but also, in relation to protection and preventive conservation and energy sustainability, the necessity to control the usable energy (the quality of light), deriving from the sun and the sky and from all the selected artificial light sources, used in any proposed sustainable lighting design. The proposed lighting design is sustainable because it aims not only at quality, efficiency and efficacy solutions (i.e., energy, environment, historical value and lighting) but, at the same time, the philological reconstruction and architectural reconfiguration of the internal space of the building (existing or newly designed) that in this research is a historical church converted into a university library.

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