Adaptive reuse, refurbishment and conservative rehabilitation of Cultural Heritage by means of Quality and Energy Sustainable Lighting.

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Abstract. Sustainable lighting designs, with a view to achieve an adaptive reuse, refurbishment and conservative rehabilitation of cultural heritage, focusing on lighting quality, mainly obtained from the optimal use of natural light combined with artificial one, is the main aim of our present research. A historical Florentine monastery, which was turned into a university library, i.e. Santa Marta University Library in Florence, was used as a pilot project. Energy saving, natural light control combined with artificial light regulation, sustainable and quality lighting by means of optic fiber textile integration, acted as fundamentals of the proposed sustainable adaptive, non-invasive, reversible and easily removable lighting design. The integrated use of natural light with LED systems and optic fibers by means of a command structure made with supervision and home automation systems based on Konnex, the first open building automation standard, allows lighting solutions for quality and environmental and energy sustainability in cultural heritage. Results showed that the proposed methodological approach allows lighting proposals with the aim of building adaptive reuse, based on architectural structure optimal use, historical–philological reading of the indoor environment, cultural heritage (CH) preventive protection and conservation, but also people and works of art “health and well-being”.

1. Introduction
Building sector presents the greatest energy saving potential, according to the EU Energy Efficiency Plan 2011 [1]. In this contest, energy control is the fundamental for energy and environmental sustainability of historical buildings and preservation and enhancement of their cultural, historical and architectural value [2,3]. The current policy, legislation, guide lines and standards are oriented to the efficient/sustainable energy use that involves lighting. [4-8]. Recent researches have highlighted different methods used for identifying energy-efficiency operations for heritage buildings [2,3,8,9].

The complex principle of the “Adaptive re-use of the built heritage” basically shows that it is always possible to modify the functional and distributive use of the indoor environment of any historical building, even when it has a strong cultural, social and religious value [7-10], that, if achieved within a sustainable lighting project also for a “smart” renovation, can contribute to remarkable energy and economic results, CH enhancement and protection, environmental
sustainability and adaptive re-use [10]. Starting from recent studies [9], in the work presented here, sustainable lighting design, aimed at preventive conservation and energy saving, was based on advanced technical textiles application. Results showed that the proposed methodological approach can be used for sustainable lighting solutions based on the adaptive re-lighting design of historical buildings, maximizing natural light use and control, with a view to the well-known principles promoted by the EU [10].

2. A method for quality and sustainable lighting

Our present work is a deepening of previous studies [9] and proposes a method for quality and sustainable, adaptive re-lighting design that can be applied to any historical building, cultural heritage cases, but also existing old buildings and current designs, guaranteeing the optimal use and control of natural light and preventive conservation.

It is based on these crucial phases: 1) data collection on historical references, limits and constraints due to current standards, external ambient climate, architectural-functional aspects and different uses of the ambient; 2) technical data on the existing lighting system and evaluation of the possible recovery and re-use of the existing electrical, suspending and control systems; 3) existing luminous climate assessment by experimental measurement on natural and artificial light; 4) building modelling and lighting simulation; 5) results analysis and comparison with current standards; 6) new lighting proposal by means of adaptivity, sustainability and reversibility concepts, by recovering of the space meaning and the historical-philological memory of the environment, finding lighting scenarios referring to the historical building/environment and its existing use, restoring its original architectural features, identifying different volumes and paths.

The method was implemented by a pilot project to assess its effectiveness in finding sustainable lighting solutions based on natural light correct and effective control for its optimal mingling with the artificial one, visual comfort, energy consumption and costs reduction (including those related to maintenance) and compliance with the standard limit values. The former minor seminary chapel, that is today a university library (i.e. currently Santa Marta library) was the case study (Fig.1). The 3D model of the environment with the existing lighting system, built up in [9], was used. The whole building and library belong to CH and are listed. The library is 10.93 m in length, 12.43 m in width and 9.82 m in height; the reading room is 22.93 m in length, 12.43 m in width and 10.62 m in height.

The natural light access is from vaulted openings placed in the highest part of the two side walls of the church: i.e. 29 single-glass windows placed at a height of 7.60 m from the floor: eight on the East and eight on the West walls, and 13 on the walls in the apse. The validated lighting simulation models obtained in [9], were used as starting base for the new proposal by using the commercial software Dialux-Evo-8.2.

The new lighting proposal was based on reversibility, easy maintenance and possibility of disassembly and removal of all the elements/components. Higher performances, quality and efficiency of the new LED systems is clearly visible, comparing the existing (Table1) with those used (Table 2: values are referred to fundamental metrics used for the LEDs performance evaluation [11-13]). The
polymeric optical fiber, known also as “smart textiles” [14,15] were integrated in the new lighting.

Light sources of the fiber optic textiles were both natural and LED lighting.

3. Lighting modelling and simulation

The new lighting solution was non-invasive and did not require any other intervention on the vaulted windows, walls or ceiling for natural light control: existing transversal electrified tracks were re-used for the suspension and fixing of two sail systems made of the optic fiber textiles, which provide homogeneous light distribution and diffusion in their lower part towards the environment below, and diffuse reflection from the upper part towards the ceiling. The main lighting scenarios, identified in [9], i.e. museum-philological-historical and functional library and then at 100% working condition, connected to the reading/writing zone of the nave and aisles were studied: optic fiber textile systems and LED sources were modelled; each LED was checked for beam and aiming angle, position and connected regulation system used (Table 2).

Table 1. Technical and photometric data of the existing artificial lighting system

| Commercial name | Lamp type | Control System | Luminous flux [lm] | Power [W] | Correlated colour temperature [K] | N. installed luminaries | Height from floor [m] |
|-----------------|-----------|-----------------|-------------------|-----------|-----------------------------------|------------------------|----------------------|
| 3F LINDA        | LED       |                 | 5200              | 58        | 3000                              | 6                      | 3,00                 |
| Steel LED       | LED       |                 | 2145              | 58        | 5000                              | 8                      | 6,51                 |
| Afrodita        | LED       |                 | 6600              | 70        | 3000                              | 6                      | 3,34                 |
| Canes           | Compact fluorescent |        | 1500              | 36        | 4000                              | 6                      | 4,50                 |
| Damp Proof LED  | LED       |                 | 1000              | 39        | 4000                              | 4                      | 2,20                 |
| F30 LED         | LED       |                 | 2000              | 150       | 4000                              | 2                      | 6,00                 |
| Tubular         | Compact fluorescent |        | 5000              | 49        | 2000                              | 32                     | 6,51                 |

Table 2 Technical and photometric data of the new proposed artificial lighting system

| Commercial name | Lamp type | Control System | Luminous flux [lm] | Power [W] | Ra | Rf | Rg | Correlated colour temperature [K] | Number installed lamps | Height from floor [m] |
|-----------------|-----------|-----------------|-------------------|-----------|----|----|----|-----------------------------------|------------------------|----------------------|
| Optec Wallwasher| LED       | DALI            | 511               | 8,6       | 92 | 90 | 100 | 3000                              | 8                      | 5,51                 |
| Optec Washer    | LED       | DALI            | 4685              | 36        | 92 | 90 | 99  | 4000                              | 4                      | 6,51                 |
| Parscan Zoom    | LED       | DALI            | 630               | 6         | 92 | 90 | 100 | 3000                              | 14                     | 5,51                 |
| Parscan Zoom    | LED       | DALI            | 1161              | 14        | 92 | 90 | 99  | 4000                              | 8                      | 6,51                 |
| Lucy            | LED       | DIMMER          | 221               | 13        | 92 | 90 | 100 | 3000                              | 18                     | 1,50                 |

Referring to the fundamental metrics [11-13] and to the sustainability and adaptivity concepts, the design choices concerning selection and positioning of LED sources, were the following: LEDs on display case, designed for the exhibition scenarios as defined in [9], working and dimmable respect the limit values suggested in [4-7]; presence sensors for the whole church in relation to the museum lighting scenario; workstations with an "on board" element in order to reduce energy consumption, guarantying high removability and reversibility, as well as optimal specific lighting for visual tasks; spotlights installed on the existing electrified tracks for the reading zone with a tilt angle of 30° providing the artificial light source of the optic fiber textiles and which can be custom made considering a ligh flux of 100 lm/m²; wall-washers LEDs for narrow beam grazing lighting along the two perimetral walls in the zone between the apse and the two sail systems; spotlight LEDs with a tilt
angle of +30° and -30° depending on display case type and position for the museum zone. Solar radiation and daylight were assessed by the calculation of the hourly variation of the incidence angle on the splayed arched windows using the method suggested in [16]. For simulations the transparence index results were used and suggested “asymmetrical” artificial light sources for the two sail systems of optic fiber textile. Due to the asymmetry in the intensity distribution of natural light, two different control and regulation groups for the dimming LEDs, installed in the optic fiber textiles, were designed. At the entrance zone and in the centre of the church (i.e. in the nave zones) emergency lights were connected to the electrified tracks. Taking into account the natural light availability, different dimming systems were used for LED sources grouping luminaires in different control groups: this choice provides important energy savings guarantying light quality, in compliance with [4,6,7].

4. Results and discussion

Simulation results show the efficiency and efficacy of the adaptive and sustainable lighting solutions. The dimensionless Modelling index (M), a fundamental metric suggested in [11,17], due to the important dimensions of the environment in terms of height, floor area and total volume, was evaluated for indoor lighting by means of a congruently adaptation of the calculation method. It was evaluated for the two new lighting scenario, in the precautionary condition of mix between the highest levels of natural and artificial light (i.e. artificial lighting system operating at 100% without dimming and control and at 10 a.m.) and referring to 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 (Esc) evaluation. M index value for the whole library/reading/apse zone, is within the limits [18,19] which is the range 0.8-1.3. Table 3 shows the M index results that prove light optimal mix, good distribution and uniformity, and goodness of light modelling.

| Table 3. Illumination and Modelling Index value – new lighting design |
|---------------------------------------------------------------|
| **Parameters** | **100% working** | **Museum-Philological History** | **Functional Library** |
| Apse Esc (1,2m) lx | 59,0 | 58,9 | 46,6 |
| Apse Esc (1,6m) lx | 63,4 | 63,3 | 52,7 |
| Apse Ev (1,2m) lx | 70,7 | 70,7 | 57,9 |
| Apse Ev (1,6m) lx | 73,2 | 73,2 | 63,6 |
| Reading Room Esc (1,2m) lx | 125 | 123 | 137 |
| Reading Room Esc (1,6m) lx | 116 | 125 | 124 |
| Reading Room Ev (1,2m) lx | 160 | 155 | 168 |
| Reading Room Ev (1,6m) lx | 144 | 153 | 153 |
| Modelling Index (M=Esc/Ev) Apse (1,2 m) | 0,83 | 0,83 | 0,8 |
| Modelling Index (M=Esc/Ev) Apse (1,6 m) | 0,87 | 0,86 | 0,83 |
| Modelling Index (M=Esc/Ev) Reading room (1,2 m) | 0,80 | 0,80 | 0,81 |
| Modelling Index (M=Esc/Ev) Reading room (1,6 m) | 0,80 | 0,82 | 0,81 |

| Table 4 Illuminance values (lx) - new lighting design |
|------------------------------------------------------|
| **Reading Plane** | **Desk-reception Plane** | **Apsen Plane** |
| (lx) | (lx) | (lx) |
| $E_{\text{min}}$ | 74 | 72 | 123 |
| $E_{\text{max}}$ | 526 | 473 | 171 |
| $E_{\text{mean}}$ | 204 | 187 | 160 |

Table 4 shows the illuminance values on the work planes and vertical plane of all the open shelved books, under the two optic fiber textile sail systems: mean illuminance level is always in the range of 30-50 lx during morning, i.e. within the limits suggested [18,19] (Table 4). Table 4 provides also minimum, maximum and mean illuminance values, for the Reading plane, Desk-reception plane and Apse-plane, calculated on the working level at 0.75 m, in precautionary conditions with all the luminaries working at 100% and highest value of external solar radiation. In Table 5 luminance
uniformity and its specific values are shown. The contrast rendering factor for vision and perception, was calculated by the ratio between the luminance for two work planes of two desks (L2) taken as tests and the luminance of the background (L1; the floor been taken as reference because the most important surface from the lighting quality point of view. These work planes correspond to the worst lighting conditions in the existing state: the first desk (desk_left) is on the left side of the library and in darkness condition, and the second (desk_right) is on the right side under the higher illuminance values due to natural light. Results in Table 6, show that the new lighting design ensures optimal mix of natural and artificial light, luminance ratios homogeneity and the contrast factor values, for both the considered work planes, in compliance with [4,5,6,18,19]. Energy performance and efficiency of the lighting proposal, for all the lighting scenarios, was evaluated by means of the Lighting Energy Numeric Indicator (LENI) assessment, total energy consumption and costs [5,6]. Taking into account the operating conditions of the regulation system (Table 7) designed for each control group of connected LED group, the average percentage incidence of the control/regulation system on the energy consumption of all the lighting scenarios is 3,7. The appreciable LENI reduction, lower annual energy consumption and costs can be noted (Table 8). Important comparisons between results obtained for the functional-library scenario both for the existing conditions and new lighting design, with LED system operating at 100% and at 10 a.m. with maximum natural light illuminance levels, are provided in Fig.3: optimal combination between natural and artificial light can also be noted. Fig. 4 provides results of new lighting design for functional-library scenario, obtained for cautionary conditions: 10 a.m. and 6 p.m. with mixing between natural and artificial light and all LEDs working 100%.

Table 5. Luminance values (cd/m$^2$) - new lighting design

|                    | East Wall | West Wall | Apse Wall | Reading Room Floor | Apse Floor | Whole ceiling |
|--------------------|-----------|-----------|-----------|--------------------|------------|---------------|
| **Functional Library** |           |           |           |                    |            |               |
| L$_{\text{min}}$    | 0,20      | 0,6       | 1,14      | 0,06               | 0,76       | 0,37          |
| L$_{\text{max}}$    | 21,8      | 30,2      | 10,9      | 4,70               | 4,25       | 2,08          |
| L$_{\text{mean}}$   | 9,47      | 12,7      | 6,6       | 2,26               | 2,01       | 0,86          |
| **100% working**    |           |           |           |                    |            |               |
| L$_{\text{min}}$    | 0,33      | 0,6       | 1,14      | 0,06               | 1,6        | 0,37          |
| L$_{\text{max}}$    | 21,9      | 29,7      | 11,3      | 4,73               | 4,55       | 2,14          |
| L$_{\text{mean}}$   | 9,66      | 13        | 8,43      | 2,26               | 2,26       | 0,89          |
| **Existing State**  |           |           |           |                    |            |               |
| L$_{\text{min}}$    | 0,1       | 0,001     | 1,65      | 0,005              | 0,12       | 0,001         |
| L$_{\text{max}}$    | 72,7      | 72,5      | 36,43     | 14,6               | 16,3       | 11,2          |
| L$_{\text{mean}}$   | 12        | 17,2      | 14,30     | 6,02               | 4,44       | 3,06          |

Table 6. Value of the contrast rendering factor – new lighting design

|                   | L$_2$ (cd/m$^2$) | L$_1$ (cd/m$^2$) | C   |
|-------------------|------------------|------------------|-----|
| Desk 01 (morning) | 3,3              | 1,3              | 1,54|
| Desk 02 (morning) | 2,9              | 1,0              | 1,9 |
| Desk 01 (evening) | 3,3              | 1,1              | 2,0 |
| Desk 02 (evening) | 2,9              | 0,9              | 2,2 |

It can be noted that for all the scenarios, the proposed lighting solutions guarantee visual comfort and ergonomics with absence of glare phenomena. The lighting solution for the functional library scenario, assessed at 2 p.m. as a cautionary choice, because of the maximum natural light incoming combined with full working conditions of the artificial light sources, provides uniform distribution of luminance and illuminance (Fig.4). The uniform distribution of illuminance and luminance levels provided only by natural light was analysed: the integration of the two optic fiber textile sail systems with natural and artificial (LED sources) light, guarantees the absence of any glare phenomena and quality of vision and perception especially when solar radiation get to the highest illuminance values (Fig.5). Considering the illuminance and luminance levels only due to the artificial lighting system working at 100%, in the evening (at 6 p.m. without natural light) the quality and sustainability of the new lighting design is guaranteed by the efficient and effective control/regulation system and the
integration of the optic fiber textiles with the high performing LED systems. In Fig. 6 the functional-library scenario results are shown. Fig. 7 shows, as an example and with different views, the new lighting for the museum-philological-historical scenario, obtained at cautionary conditions with mixing between natural and artificial light and all the LED luminaries 100% working, at 10 a.m.

### Table 7. Control/regulation system operating conditions for all the different scenarios – lighting proposal

| Proposed lighting scenarios          | LED reading room | LED media room | LED reading room | LED apse zone | LED cases |
|-------------------------------------|-----------------|----------------|-----------------|---------------|----------|
| Functional-library                  | 100 %           | 100 %          | 100 %           | Off           | off      |
| Museum-philological-historical      | Off             | Off            | 100 %           | 100 %         | off      |

### Table 8. Lighting Energy Numeric Indicator, Energy consumption and costs – new lighting design

|                             | Existing State | 100%          | Museum-Philological-History | Functional Library |
|-----------------------------|----------------|---------------|-----------------------------|--------------------|
| Consumption (kWh/year)      | 10300-15100    | 3800-5700     | 2500-3600                   | 3400-5150          |
| Costs (€/year)              | 3093-4528      | 1139-1709     | 800-1200                    | 1025-1538          |
| LENI (kWh/year/m²)          | 22-23          | 9-14          | 6-8                         | 8-12               |

Figure 2. Illuminance (lx) and luminance (cd/m²) distribution at 10 a.m. for functional-library scenario: (top left) illuminance at the existing state; (top right) illuminance of the new lighting; (bottom left) luminance at the existing state; (bottom right) luminance of the new lighting.

5. Conclusions

Results showed that it is always possible to combine the adaptive re-use concept with adaptive re-lighting design and health, protection and preventive conservation of works/objects of CH in historical buildings, by means of a natural lighting design based on its optimal mix with artificial light and effective control systems.

The proposed method can be a useful tool for adaptive and sustainable re-lighting design also oriented to the “Human Centric Lighting (HLC)” [20,21]. Following these basic concepts, our findings highlighted that sustainable, reversible and adaptive re-lighting solutions, oriented to the integration of HCL with preventive conservation of cultural heritage, can be achieved by the optimal mix between...
natural and artificial light combining efficient control and dimming systems with innovative application of LED technologies and smart-advanced textiles.

Figure 3. New lighting design for the functional-library scenario at cautionary conditions with mixing between natural and artificial light and all the LEDs 100% working at 10 a.m.: (top left) false colours render of illuminance values (lx); (top right) false colours render of illuminance values (cd/m²); (bottom left) rendering at 10 a.m. and (bottom right) rendering at 6 p.m.

Figure 4. Illuminance values (left; lx) and luminance values (right; cd/m²) at 10 a.m. – only natural light (artificial light off) for the functional library scenario design; a view below the two sails system with optic fiber textile.

Figure 5. Two rendering views: from left to right rendering of new lighting design of the functional-library scenario obtained with all the LEDs at 100% working conditions in the evening at 6 p.m. (without natural light).
Figure 6. Two rendering views: from left to right rendering of new lighting design (museum-philological-historical scenario) obtained at cautionary conditions with mixing between natural and artificial light and all the LEDs 100% working, at 10 a.m.

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