Sustainable lighting for cultural heritage: a pilot study for evaluating the exhibits’ display inside historical buildings.

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Abstract. Lighting cultural heritage is a complex task that requires considering the conservation needs of the exhibits and visitors’ visual comfort. However, these needs are often in contrast. In addition, whenever the exhibitions are displayed inside historical buildings, the task further complicates, as lighting designers must face and respect the architectural character of the host building. They have two mean of work: static and dynamic analysis. The former uses the Daylight Factor (DF) while the latter requires a prolonged and expensive measurement campaign. Both analyses present advantages and shortcomings: the DF approach is easy and fast, but it implies many oversimplifications whereas the annual approach provides accurate results but is time and money-consuming. In this paper the authors analyse a case study with both methods. The case study is the Cetacea’s Gallery of the Charterhouse of Calci (PI). The findings of this research demonstrate that the annual approach is preferable, despite its costs, and that the static approach should be used just for first instances analyses. The research pointed out the necessity of a standardized procedure of evaluation that would allow lighting designers to confront possible interventions and find the most adequate to solve the conservation and comfort issues of the case in exam.

1. Introduction

Worldwide, but in particular in Italy, it often happens that historical buildings -such as churches, libraries, monasteries and castles- are converted for different purpose, once their original one wears out [1-4]. The most common re-functionalization is linked to tourism and cultural heritage display. It may appear that historical buildings are well suited for this use, due to their intrinsically evocativeness and thanks to the fact that re-using historical buildings helps fighting the degradation and abandonment while promoting art and culture. However, this operation implies some difficulties: first of all, historical buildings may not be accessible in all of their parts by people with disabilities; secondly the energy consumption of these kind of buildings must be carefully evaluated (in order to reduce the energy needs); and finally, because “promoting art and culture” has a deeper meaning. The article 2, comma b of the Decree of the Italian Ministry of Cultural Heritage states[5]: “The National Museal System aims to: […] guarantee the access to cultural heritage to the users, and to further develop heritage conservation, through the definition of a standardized and verifiable fruition level of cultural buildings, of uniform and confirmable modalities for the conservation and enhancement of shared buildings, locations, museal collections, ethics and policies of the museums, in compliance with the autonomy of the single institutes.” This means that every building that is designed, or converted, into an exhibition space must guarantee the exhibits’ availability and their conservation, by offering adequate display conditions. However, even if historical buildings are often used for this purpose, it is common they fail adequate criteria for exhibits’ display. From the conservation point of view light and thermo-hygrometric conditions are the main factor of risk for exhibits [6]. Daylight in particular, being rich of UV and IR radiation is the most hazardous light source [7, 8]. Nevertheless, from the visual comfort point of view, it is the most favourable. In addition to the cultural heritage conservation point of view, it is important to consider that light can deeply influence the visitors’ enjoyment and understanding of the artworks [9], and visitors’ visual and colour perception [10], and therefore it must be carefully studied.
2. Research aim

This research ponders the sustainability of two different approaches to cultural heritage lighting analysis. The first is based on the Daylight Factor (DF) while the second is based on measurement campaign. With the term “sustainable lighting” we refer to every action that implies the exploitation of resources. For those actions to be sustainable they must enhance the exploited resources’ current and future potential to meet human needs [11]. For what concerns cultural heritage, the exploited resources are the exhibit: in fact, light is necessary in order for the visitors to see them, but its damage must be avoided, or at least, monitored.

Figure 1. Aerial view of the Monumental Charterhouse of Calci, the Natural History Museum of The University of Pisa.

Figure 2. 3D CAD model used for the simulations: (top left) entire Charterhouse; (other images) Cetacea’s Gallery.
The two different approaches differ in costs and accuracy, in order to assess their actual sustainability those aspects must be considered alongside the conservation-related ones. The first approach relies on the DF, whereas the second requires annual measurement campaigns. The confrontation will show the advantages and shortcomings of both methods and it will provide suggestions on which method to use depending on the aim of the analysis.

3. Materials and methods

The DF-based and the Measurement-based approaches were applied to a case study: the Cetacea’s Gallery of the Monumental Charterhouse of Calci (Figures 1, 2). The Gallery was chosen for the architectural value of the host building and for the massive presence of large full-height windows on both north, south and west oriented façades. The analyses were run with software simulations (using Grasshopper’s environmental plugins) and with on-site measurements. The 3D CAD model (Figure 2) was based on an architectural survey of the Charterhouse performed by School of engineering of the University of Pisa, and it was realized using Rhinoceros. The materials’ properties (Table 1) were defined using Colour-picker-for-Radiance [12]. To validate the model, the horizontal illuminance was recorded using a photoradiometer, composed of data logger Delta Ohm HD2102.2 equipped with LP 471 PHOT probe. The probe is able to measure the illuminance from 0 lx to 20000 lx, with a resolution of 1 lx and a linearity deviation lower than 1%.

| Material characteristics of the modelled geometries |
|----------------------------------------------------|
| **R reflectance**                                  |
| Tiled Floor                                       |
| 0.36                                               |
| Plastered Walls                                   |
| 0.36                                               |
| Ceiling                                           |
| Tiled ceiling                                     |
| 0.80                                               |
| Wooden beams                                      |
| 0.32                                               |
| Metal frame                                       |
| 0.34                                               |
| Metal beams                                       |
| 0.29                                               |
| Windows                                           |
| Panels                                            |
| 0.75                                               |
| Glass mullion                                     |
| 0.89                                               |
| **G reflectance**                                 |
| Tiled Floor                                       |
| 0.27                                               |
| Plastered Walls                                   |
| 0.15                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.73                                               |
| Metal frame                                       |
| 0.25                                               |
| Metal beams                                       |
| 0.13                                               |
| Windows                                           |
| Panels                                            |
| 0.75                                               |
| Glass mullion                                     |
| 0.89                                               |
| **B reflectance**                                 |
| Tiled Floor                                       |
| 0.22                                               |
| Plastered Walls                                   |
| 0.10                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.71                                               |
| Metal frame                                       |
| 0.23                                               |
| Metal beams                                       |
| 0.10                                               |
| Windows                                           |
| Panels                                            |
| 0.75                                               |
| Glass mullion                                     |
| 0.89                                               |
| **Specularity**                                   |
| Tiled Floor                                       |
| 0.00                                               |
| Plastered Walls                                   |
| 0.00                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.00                                               |
| Metal frame                                       |
| 0.00                                               |
| Metal beams                                       |
| 0.30                                               |
| Windows                                           |
| Panels                                            |
| -                                                  |
| Glass mullion                                     |
| -                                                  |
| **Roughness**                                     |
| Tiled Floor                                       |
| 0.00                                               |
| Plastered Walls                                   |
| 0.00                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.09                                               |
| Metal frame                                       |
| 0.20                                               |
| Metal beams                                       |
| 0.20                                               |
| Windows                                           |
| Panels                                            |
| -                                                  |
| Glass mullion                                     |
| -                                                  |
| **Average diffuse transmittance**                 |
| Tiled Floor                                       |
| -                                                  |
| Plastered Walls                                   |
| -                                                  |
| Ceiling                                           |
| -                                                  |
| Wooden beams                                      |
| -                                                  |
| Metal frame                                       |
| -                                                  |
| Metal beams                                       |
| -                                                  |
| Windows                                           |
| Panels                                            |
| 0.75                                               |
| Glass mullion                                     |
| 0.89                                               |
| **Average diffuse reflectance**                   |
| Tiled Floor                                       |
| 0.29                                               |
| Plastered Walls                                   |
| 0.21                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.75                                               |
| Metal frame                                       |
| 0.27                                               |
| Metal beams                                       |
| -                                                  |
| Windows                                           |
| Panels                                            |
| 1.52                                               |
| Glass mullion                                     |
| 1.52                                               |
| **Recommended values**                            |
| Tiled Floor                                       |
| 0.30                                               |
| Plastered Walls                                   |
| 0.31                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.27                                               |
| Metal frame                                       |
| -                                                  |
| Windows                                           |
| Panels                                            |
| -                                                  |
| Glass mullion                                     |
| -                                                  |
| **Deviation from recommended values**             |
| Tiled Floor                                       |
| 0.01                                               |
| Plastered Walls                                   |
| 0.11                                               |
| Ceiling                                           |
| Wooden beams                                      |
| 0.00                                               |
| Metal frame                                       |
| -                                                  |
| Windows                                           |
| Panels                                            |
| -                                                  |
| Glass mullion                                     |
| -                                                  |

4. Analysis of the case study

4.1 Brief Historical analysis

The Charterhouse was funded in 1366 as a Carthusian monastery thanks to wealthy Pisan families’ donations [14]. Nowadays the original structure has almost been completely lost due to 7 centuries of changes. The major modifications started during the priorate of Alfonso Maria Maggi between the 18th and 19th centuries [15-19], and followed during the 20th one, due to WWI and WWII [20]. In fact, first Maggi renewed the monastery’s typical and simple Carthusian style, then the Charterhouse was occupied by the 32nd field-artillery (1893-1915), converted into a backup field hospital (1915) and later into an emergency storage for artworks in case of war (1939). Finally, in 1979 the last monks left the monastery and the Charterhouse was partly donated to the University of Pisa which in 1981 inaugurated the Natural History Museum. The Cetacea’s Gallery (Figures 2, 3) corresponds with second floor of the
ex-barn of the monastery, the rectangular plant measures 7x110m for a total floor surface of 699m² and a volume of 3426m³. The space is articulated in 21 bays, marked by brick columns. Each bay presents 2 large and full-height windows on both north and south orientation, and in addition there is a wide arched window on the west terminal wall. The ratio of windowed to floor area is 67%. The Gallery hosts the most important cetacean skeletal collection for number of species in Italy, it is the only collection worldwide displaying at the same time the skeletons of the 3 biggest non-extinct animals [21]. The collection is formed by 28 skeletons, 11 life-side models, 36 scaled models and 9 thematic areas.

Figure 3. The Cetacea’s Gallery collection: in green the skeletal specimen; in blue the life-sized models, in orange the thematic areas. (top) Longitudinal section; (bottom) Planimetric view.

4.2 Normative review

As mentioned above lighting designers can use two approach for their analysis: DF-based or annual measurements-based. For what concerns the first one, the UNI/Pdr 13-2, 2019 version [22], provides a procedure to evaluate the energetic and environmental sustainability of buildings, the procedure is developed by the Italian Institute for Innovation and Transparency in Tenders and Environmental Compatibility (ITACA). This procedure suggests DF upper limits depending on the room intended use. For museums and exhibition halls no values are provided (Table 2), nevertheless in the previous version (UNI/Pdr 13-2, 2015 version [23]) it was suggested that DF≤1% for this casuistry (Table 3).

### Table 2 – DF suggested upper limits depending on the room intended use [22]

| Room intended use                                    | Limit value for DF |
|------------------------------------------------------|--------------------|
| Single and open space offices                        | 2%                 |
| Meeting rooms                                        | 2%                 |
| Creches, kindergartens and nurseries                 | 5%                 |
| Classrooms                                           | 3%                 |
| Music rooms, Laboratories                            | 3%                 |
| Auditoriums                                          | 2%                 |
| Libraries, Reading rooms                             | 3%                 |
| Gyms, Canteens                                       | 2%                 |
| Hallways, Stairs, Distribution areas                 | 1%                 |

### Table 3 – DF suggested upper limits depending on the room intended use [23]

| Room intended use                                    | Limit value for DF |
|------------------------------------------------------|--------------------|
| Offices                                              | 2%                 |
| Hallways, Stairs, Distribution areas                 | 1%                 |
| Commercial buildings                                 | 2%                 |
| Industrial buildings                                 | 1%                 |
| Hotel rooms                                          | 1%                 |
| Restaurants                                          | 2%                 |
| Libraries, Reading rooms                             | 2%                 |
| **Exhibition halls, Museums**                         | **1%**             |
For what concerns the annual approach the standards to refer to are the EN 16163:2014 [6] and the Decree of the Italian Ministry of Cultural Heritage [24]. These standards provide methods to perform the measurements and suggest two metrics for monitoring the conservation of exhibits. These metrics are Maximum illuminance ($E_{\text{max}}$) and the Total annual exposure (LO). $E_{\text{max}}$ and LO upper limits depend on the photosensitivity of the exhibits and vary between the two standards, for bones and skeletal specimen the more restricting are the national ones, which correspond to $E_{\text{max}}=150 \ \text{lx}$ and LO=$0.5 \ \text{Mlx*}\text{h/year}$.

### 4.3 DF-based approach

The DF can be calculated using one of the equations provided by Italian standard UNI 10840 [25]:

\[
\begin{align*}
\text{DF} & = \frac{\sum_{i=1}^{n} \varepsilon_i \tau_i A_i \psi_i}{S(1-\rho_m)} \\
\text{DF} & = \frac{E_i}{E_o} \times 100
\end{align*}
\]

Where:
- $\varepsilon$ window correction factor, it considers potential obstructions;
- $\tau$ transmissive index of the windows;
- $A$ surface of the windows ($\text{m}^2$);
- $\Psi$ correction coefficient, it considers the retreat of the windows to the external facade;
- $S$ sum of the interior surfaces ($\text{m}^2$);
- $\rho_m$ average refractive index of the interior surfaces;
- $E_i$ illuminance inside the room, shaded from direct sunlight, under overcast sky conditions (lx);
- $E_o$ illuminance outside near the windows (lx).

The advantage of this method is that the calculations are easy and do not require specific surveys. In fact, the only information necessary are: the geometry of the room; the geometry of potential obstructions; the geometry, the transmission index, and the surface of the windows; the refractive indexes of the interior surfaces. These information can be easily acquired, moreover the indexes are tabulated depending on the materials and their colours. It should be noticed that (1) does not depend nor from the windows orientation, nor from date or time [26]. In addition, if (2) is used, $E_i$ must be recorded under overcast sky conditions [26]. However, the actual representativeness of those meteorological conditions for the site in exam is not implicit. In case study the DF was calculated using (1), in addition the DF value was calculated using software simulations. Results are shown in Table 4.

| Table 4 – DF analyses results |
|------------------------------|
| Applying (1) | Based on the simulations | Deviation between (1) and simulations |
| 11.20% | 9.73% | 1.47% |

### 4.4 Measurements-based approach

For the pilot study it was impossible to directly measure the total annual exposure using annual measurements, due to time and economic-related issues. Unfortunately, as aforementioned, that is the shortcoming of this approach. However, the LO was calculated using software simulations. This approach (may it be based on simulations or on-site measurements) provides more accurate results. The analysis period corresponded with the entire year, in fact exhibits in the current display exhibits are exposed to daylight from sunrise to sunset 12 months per year. The simulations were run using Honeybee+ and Ladybug (environmental analysis plugins for Grasshopper). Those plugins use climate-
based data, meaning that simulations consider the actual meteorological conditions for the site in exam and provide reliable results. Results are shown in Table 5.

| Surfaces facing north | Surfaces facing south |
|-----------------------|-----------------------|
| Simulations results   | 12.72 Mlx*h/year      | 27.19 Mlx*h/year      |
| Deviation from limits set by [24] | +12.22 Mlx*h/year | +26.69 Mlx*h/year |

### 4.5 Results discussion

Both approaches indicate that the Gallery is over-lit. However, the results obtained using the DF approach provide few information: such a high value indicates that the Gallery is daylit abundantly. Unfortunately, we gain no insight on the actual lighting conditions on the exhibits. This means that the DF approach is not well suited for in depth analyses, even if is acceptable for first-instance evaluations. On the contrary the second approach provides useful information that lighting designers can confront to standards’ requirements. Still, for this approach to be applied one would need to accept the costs and length linked to annual measurements campaign. It is true that this step can be circumvented using reliable simulations, however these must always be validated and therefore measurements campaign cannot be totally avoided.

### 4.6 On-site measurements

The simulations’ accuracy was validated using on-site measurements: illuminance was recorded on a horizontal plane placed 1.00m above floor level. Measures were taken on December the 6th under overcast sky conditions (Figure 4) using Delta Ohm 2102.2 luxmeter from 10:23 to 12:25. The mean illuminance value, obtained through the averaging of the measurements, is $E_m=310$ lx, while the outdoor illuminance is $E_o=3126$ lx. Applying (2) one would obtain:

$$DF = \frac{310}{3126} \times 100 = 9.93\%$$

Figure 4. Sky condition, photos taken facing north (a) and south (b).
The error one would perform by using (1), or by using the simulations, instead of the value obtained through (3) is shown in Table 6. These results demonstrate that climate-based simulations are reliable, therefore they can be used for the estimation of LO without recurring to annual measurements. Nevertheless, the on-site measurements are necessary to at least validate the simulations’ accuracy.

| Table 6 – DF deviation from the measured values |
|-----------------------------------------------|
| Applying (1) | Based on the simulations |
| DF results   | 11.20% | 9.73% |
| DF deviation from (3) | +1.27% | +0.20% |

5. Conclusions

The pilot study demonstrates that both the DF and the Measurements-based approaches can be used, to acquire information on the exhibits’ lighting conditions. However, due to the oversimplifications of the first, it is not advisable to use the DF approach for in depth analyses. This metric is not orientation or time-dependant and implies a fixed sky model that may not correspond with the actual meteorological conditions of the site in exam. On the contrary for such analyses the Measurements-based approach is recommendable, even though it requires major costs for the measurement campaign: the need to acquire sensors is likely to occur. In fact, instead of relying on an operator, it is more practical to use dataloggers to register the annual values. Considering the sustainability of the two approaches it appears clear that the second one is most favourable: the economic costs are compensated by the accuracy of the data acquirable. Once again it is paramount to state that sustainable lighting cannot be confined to the economic sphere, but it must consider the exploitation of the exhibits (considered as resources). Finally, the simulations demonstrate that the exhibits inside the Gallery are in danger: the deviation from the LO upper limit set by standard is extremely relevant (+24.4% and +53.4% respectively for the north and south oriented surfaces). Therefore, an intervention to secure the exhibits is urgent. The authors believe that a scientific standardized procedure to evaluate the exhibits’ display conditions and to confront potential interventions is desirable. Such a procedure would allow to follow a repeatable approach, meaning that various courses of action could be compared to find the most adequate one. The authors are currently developing a proposal for such a standardized methodology. The methodology will rely on climate-based daylight simulations and on-site measurements to validate these previsions. It will consider the requirements for the conservation of the exhibits and for the comfort and safety of visitors.

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