Lighting of Museums and Art Galleries

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Abstract. A museum is a place where people can explore and learn the past, the present and the future of culture and science. Amongst the other technical systems, the lighting equipment must satisfy a number of requirements. For each project, lighting designers must face challenges in order to encompass the given specifications in a single lighting concept: protection of the artefacts, economic convenience, architectural constraints and, last but not least, the creative ambitions of the artist. This paper analyses the lighting environment of a real art gallery with the aim to identify a satisfactory solution in terms of enjoyment, artefact preservation and energy consumption. By means of a simulation software, suitable general and spot lighting devices are chosen to fulfil the requirements whilst avoiding damages to the artefacts, and lighting parameters are obtained to evaluate the proposed solution. The work shows that advanced LED technologies can be effectively used to modify a museum lighting environment and turn it into the classical gallery archetype.

1. Introduction

Light is a design element with the ability to modify a space without the need of changing its physical dimensions. It is an extremely versatile factor that can shape spaces or define functions without prevailing on the architectural structure. Light influences the appeal of an environment communicating different sensations, and it is so powerful that it provides dynamism to static elements.

As for the lighting, the acoustics of rooms are extremely relevant for improving the design of spaces and for evaluating the experience of the listeners [1, 2]. Furthermore, the acoustic properties of rooms are considered one of the most important cultural heritage [3, 4] at the same importance level of ancient musical instruments [5-11]

Since time immemorial, man has questioned the phenomenon of light, first relating it to divine entities, such as the god Horus in Egypt, then linking it to vision, a passage that took place with the Greeks. It was only during the Scientific Revolution of 1600, that laid the foundations of the physical theory of light recognising its phenomenological nature independent of the objects, that scientists started investigating more on this phenomenon. One of the most interesting aspects was the very nature of light, in particular to understand if it was composed by corpuscles as Newton claimed, or waves, as Huygens believed. The corpuscular model considered light as a set of very small particles moving in bundles, called rays, which follow line paths. This theory could explain the propagation of light and its reflection. The wave model, however, assumed that light is a wave capable of propagating not only in materials but also in empty space. The ability of light to propagate even in vacuum tormented physicists for a long time, until the electromagnetic theory of light was finalised by James Maxwell between 1864 and 1873, thus making the wave model the accepted one for over half a century. His theory was fully established when it was proven by Hertz's experiments in 1887. Then,
however, at the beginning of the 1900s Einstein put forward another hypothesis for which light is composed of photons. With the theory of quantum mechanics, it was possible to reconcile the two models, theorising a double nature of light, corpuscular and wave: the wave phenomenon allows to explain, for example, the propagation in the void while the corpuscular phenomenon explains precisely the interaction between light and matter. Due to its corpuscular and wave nature, light has several properties, such as wavelength and thus chromaticity, intensity and directivity. Since that times a lot of research has been made on the basic theory and applications of lighting, bringing to the development of extremely efficient light sources.

Nowadays most of human activities take place in closed spaces, which are illuminated mainly by artificial sources. For this reason, it is essential that the lighting is accurately designed.

There are several studies available in the literature where researches have shown that lighting can affect human cognitive functions and mood. Different types of light can increase or, on the contrary, decrease attention and productivity. For example, a very illuminated room can improve our productivity while dark spaces are more relaxing: therefore, not only should a lighting project have the goal to make things visible, but also aim to create the best possible conditions for the envisaged tasks, without introducing disturbs or being an obstacle to their execution. From this point of view a museum is a very peculiar space, where the visitors must sense participation in the exposition and be able to appreciate also the smallest particulars of the artefacts shown. In the next section, the role of lighting in such environments will be considered.

2. The role of light in museum environments

2.1. History of museums lighting

A museum can be illuminated in many ways, depending on its architecture and the type of exhibition (paintings, documents, statues, archaeological findings, tools, jewellery, etc.). Another categorisation can be based on the layout of the objects in the environment, depending on the willing of the artistic supervisor to create paths for the public.

If we consider the peculiarities of some contemporary museum architectures such as, for example, the Salomon R. Guggenheim Museum by Frank Lloyd Wright in New York, it is evident that light in the museum context does not only fulfil a functional role, that is to allow you to ‘see’, but has also an aesthetic function, enhancing the architectural structure itself. Despite this extremely variable outlook, there are some aspects of museums lighting responding to common needs and functions. In the modern museums, the act of seeing is the prevailing one. The sight becomes the essential sense for the aesthetic experience so that the exhibition environment tends to expel any other presence that distracts the other senses. The museum, as we know it today, was born during the eighteenth century, when various educated sovereigns and popes decided to make their collections public so to spread the culture among the population. From the eighteenth century to the present day, the structures that host the artistic heritage and the design criteria have changed considerably, following cultural and technological evolutions. Two aspects, however, have always persisted over time, thus defining the nature of the museum institution: the task of protecting from degradation and preserving the integrity of its assets and the task of properly show them to the public.

The first public museums of the eighteenth century were illuminated by natural light. Obviously, this was a necessity as artificial light sources, alternatives to natural ones, were still very primitive and, being open flame based, dangerous for the proper conservation of valuable goods. The most used architectural models, from the eighteenth century throughout the nineteenth century, were that of the gallery. This is a long corridor, which was already widely used in the sixteenth-century buildings, covered by a dome. The gallery receives light from one side by means of windows, while the centre of the room, receives light from above.

One of the first museums that used this model was the Pio-Clementino Museum in Rome, built between 1771 and 1791 by the will of popes Clement XIV and Pius VI. The Round Hall (Figure 1) is part of the so-called ‘Roman rooms’ commissioned by pope Pius VI and created by the architect Michelangelo Simonetti. It becomes the heart of the museum: it is the largest room, clearly inspired by the Roman Pantheon, with a circular plan, a coffer vault and a central opening. In addition, there are
windowed bezels in the drum, useful for enhancing the diffusion and uniformity of the light inside the space. This room will become one of the most popular models of museography for the 19th century.

Figure 1. Round Hall, Vatican Museums

Zenithal light is also present in one of the world's best-known museums, the Louvre. Established in 1793, after the French Revolution, it was actually the first museum to decree the public ownership of a cultural heritage. The aim of the museum was to open the spaces to a wider audience of users, even on Saturdays and Sundays. Initially the Louvre had a rather modest appearance and the perspective views of Hubert Robert's 1795 of the Grande Galerie (Figure 2a) show a messy and poorly lit environment with only few side windows. The paintings were often left on stands near the windows to receive better light. When, in 1803, the Louvre became the “Musée Napoléon” and Dominique Vivant-Denon was appointed director, the restoration and reorganization of the structure and collections began. One of the first interventions made by the architects Percier and Fontaine was to give a novel appearance to the Grande Galerie by creating new openings to increase lighting (Figure 2b).

Figure 2. Hubert Robert, a) The Grand Louvre Gallery between 1794 and 1796, b) The Grand Louvre Gallery after 1801

Unfortunately, it is not always possible to create new openings, and so the use of artificial lighting becomes crucial. Frequently, historical and heritage buildings are intended for cultural purposes such as libraries and museums and they need a specific, peculiar redesign regarding energy performance [12], luminous efficiency, indoor microclimate and acoustic behaviour [13]. The challenge consists of optimizing energy efficiency, also balancing costs and performance [14, 15], limiting the lighting as well as full preservation of ancient manuscripts and artworks, taking into account the limited degrees of freedom due to several constraints about the materials, the geometry, and the structures.
2.2. Conservation, fruition and energy saving

When an artificial illumination is installed in a museum, a number of factors must be kept into account [16] the main problems that must be addressed are:

- The need to limit the lighting and to control it in order not to damage the exposed goods (sensitive to the effects of light radiation);
- The need to sufficiently illuminate the environment in order to make it accessible and appreciated (if it is valuable as an historic place);
- The possibility of obtaining, with an innovative lighting project, some energy savings.

A refurbishing project that proved to be an example in terms of energy efficiency is the one made for the Wilhelm-Hack museum in Ludwigshafen, with a 70% drop in energy costs for lighting [17].

The main factors on which a correct use of lighting can lead to less energy consumption are:

- The maximum use of natural light and the use of artificial sources only as a balance to natural light;
- The use of light sources that have maximum energy efficiency. This means a high ratio between the light output and the electrical power absorbed. However, efficiency should also fulfill other requirements such as the size of the luminaires, the colour rendering and the lifetime of the lamp.
- The correct positioning of the lighting fixtures in order to ensure the most adequate use of the light emitted, avoiding glare and then assuring the users visual comfort.

A proper lighting apparatus is essential to allow optimal visibility while ensuring that its appearances are left intact [18].

The light emitted by LED spotlights makes this source a suitable replacement for spotlights featuring halogen incandescent lamps. Energy consumption over the entire service life is considerably cut. The reduced heat dissipation of LEDs also has a positive impact on operating costs: the heating loads on air-conditioning systems are significantly smaller and the power of the HVAC systems can be scaled down considerably.

Even when a LED luminaire is positioned close to an object to achieve maximum effect, it delivers more gentle lighting than conventional luminaires. This significantly reduces the risk of colour fading or damage of sensitive materials [19].

A simple change of colour temperature is an ideal way to achieve complex lighting solutions which are perfectly tuned to any art era and exhibition concept; quality of perception can also be selectively influenced in this way. The colour temperature specified during the setting up is accurately maintained even when the LED luminaire is dimmed.

Because of their extremely long service life, LEDs allow longer maintenance intervals. The long-life of LED luminaires minimizes expensive maintenance work – especially in situations where changing the lamps requires considerable effort. Museums with high ceilings or elaborately protected and secured display cases containing valuable items are just two examples where a durable LED luminaire pays back very soon. LED spotlights are designed for optimal thermal management and feature either active cooling with innovative fan technologies or passive cooling using heat dissipation solutions.

To summarise, the luminous efficiency of the latest generation of LED lamps is far higher than that of halogen incandescent lamps and is currently 80-120 lm/W depending on colour temperature. The focused light produced by LEDs is perfect for accent lighting. From a preservation of the piece viewpoint, LEDs are highly recommended because they produce negligible UV and IR radiation. Other unique characteristics of LEDs include simple dimmability and a long service life (50,000 hours until luminous flux drops to 70%, ignoring small numbers of failures).

3. Lighting quality parameters

The main quantity to evaluate lighting of any space is the illuminance $E$, measured in lux, defined as the luminous flux $\Phi$ incident on a surface $S$:

$$E = \frac{\Phi}{S} \quad (1)$$

or, in case of horizontal planes
$E_{\text{horiz}} = \frac{I}{d^2} \cos \theta \tag{2}$

Where $I$ is the intensity emitted by the source in the direction of the illuminated plane, $d$ is the distance between the source and the plane and $\theta$ is the angle between the intensity and the normal to the plane.

The minimum acceptable illuminance threshold is usually recommended according to the space category. However, in the case of museums it is determined by the display requirements [20], being the preservation of the artifacts the priority. In this respect, the recommended values depend on the materials [21]: in case of paintings, the recommended value may even depend on the technique (for example, 50 lx for watercolour, 200 lx for canvases and frescoes).

Correlated colour temperature (CCT) in kelvin is a source-related parameter known to have a strong impact on the lighting preference expressed by observers in terms of colour perception. It is defined as the temperature associated to an ideal black body radiating light chromatically comparable to the source, through Wien’s displacement law:

$$\lambda_{\text{peak}} = \frac{b}{T} \tag{3}$$

where $\lambda_{\text{peak}}$ is the wavelength at which the spectral radiance of the black body peaks, and $b$ is Wien’s displacement constant. Several studies based on surveys report that observers are usually more comfortable with neutral lighting when it comes to museum displays [22]. According to Kruithof’s studies in the mid twentieth century, a pleasant perception can be obtained by properly choosing the CCT of the source in relation to the illuminance, although several studies raised exceptions to this theory [23].

4. A case study: Palazzo Martinengo art gallery

4.1. Introduction and goals

In this section the updates of the lighting system installed in the ‘red’ room of the Tosio Martinengo Art Gallery (Brescia, Italy) will be analysed. The refurbishment tried to achieve the following objectives:

- Higher quality of light for an improved visual experience
- Better long-term maintenance
- Improved system efficiency/lower costs

We will therefore focus on the technical aspects related to the possibility of equipping a gallery with luminaire effects able to replicate a gallery environment featuring the effect of natural lighting coming from the ceiling even without the possibility to create openings on the top slab. Other aspects as the acoustics [24, 25] will be analysed in further papers. Useful information will be provided on how to adapt the spaces to different needs, keeping the dimensions of the room and understanding the benefits attainable with LED lighting systems. The lighting effect that can be achieved will be studied through simulations and 3D renderings made using DIALUX commercial software.

4.2. Context

The Tosio Martinengo Art Gallery is in an historic building placed close to Brescia city centre. The exposition is organised on two floors and the paintings are presented in different rooms distributed at the first floor (Figure 3). The red room is the one having the biggest dimensions ($21 \times 11 \, \text{m}^2$) and is marked with a red filling in Figure 3. The ceiling is placed at a height of 5 m and it is made by amber wooden beams. The ceiling does not have skylights bringing natural light in the room. The walls are lined in red velvet, while the floor is made by grey marble.
This room holds 9 old paintings from famous Italian artists like Raffaello, Foppa, Savoldo, Moretto and Romanino. The most representative part of the room is the northern wall, where the paintings shown in Figure 4a are placed. There are only two windows bringing natural light inside the room. Such windows are positioned on the northern wall and have dimensions 1.5 \times 3 \text{ m}^2. The size and orientation of these windows are not sufficient to guarantee a good illumination of the paintings even during the brightest summer days.

In order to re-create the lighting conditions typical of an art gallery, as described in Section 2.1, two artificial skylights have been created by using arrays of LED panels on the ceiling, as shown in Figure 4b. The general lighting system is integrated with spotlights for the local illumination of the paintings. The position and the orientation of the spotlights in the model are the same as the real case, and the lighting characteristics of the LED panels and of the LED spotlights used in the model are the following:

- **LED panels:** number: (6 \times 6) \times 2; electric power 18W, single panel dimensions 600 \times 600 mm, luminous flux: 2000 lumen, luminous efficacy: 110 lm/W, colour temperature: 4000 K, CRI 82, maintenance factor: 0.8. The panels have been mounted in two clusters as shown in Figure 4b. Figure 5a shows the luminous flux spectrum of the LED panels.

- **LED spotlights:** number: 9; electric power: 29W, luminous flux: 2270 lumen, luminous efficacy: 78 lm/W, colour temperature: 3000 K, CRI 92, maintenance factor: 0.8. Figure 5b shows the luminous flux spectrum of the LED spotlights.
5. Results and discussion

The simulations were made considering the contribution of the daylight given by the windows at noon of the 13th of June. Running a simulation for the daylight only the results show an illuminance at the foot of the windows around 120 lx, and a value of the same parameter for the northern wall which ranges between 10 lx and 30 lux. Such values are not satisfactory to guarantee an appropriate lighting of the artworks, even at noon. A second simulation featuring only the LED panels placed on the ceiling was run to determine the contribution of these type of lamps. The results given by DIALUX reveal illuminance values ranging from 300 lx to 380 lx for the floor, but on the northern wall the illuminance hardly reach 150 lux. Moreover, the central painting results much more illuminated than the two paintings placed at the sides. Figure 6 shows the iso-illuminance colour contour plot on the northern wall considering also the spotlights. From Figure 6 it is possible to notice that the side paintings are exposed to illuminance values very close to 200 lx. The average illuminance value is around 140 lx. The higher values are concentrated on the upper-inner sides of the artworks, so they are adequately illuminated to show the details to the public preventing at the same time too high luminous radiations which could damage the paintings. Moreover, the accent lighting given by the spotlights makes the illumination of the wall less uniform and therefore less “boring”. The luminance of the paintings is around 5.9 cd/m². The values of the UGR for the 3 paintings are lower than 10, showing no glare effects are given by the spotlights. Finally, DIALUX can make an estimation of the necessary electric power on an annual basis, which is encompassed between 950 and 1440 kWh with an annual cost ranging from 286 to 422 €/year.

Figure 5. a) luminous flux spectrum of the LED panels; b) luminous flux of the LED spotlights.

Figure 6. Iso-illuminance curves of the “red room” northern wall.
6. Conclusions
The illumination of museums is a challenge from the technical point of view, which finds the ideal solution, for expositions with paintings, in the so called ‘art gallery’ solution. Such kind of space is characterised by wide windows and skylights placed on the ceiling of the room, which usually has a stretched shape. It is worth noting that it is not always possible to realise such type of illumination, since not all the rooms can feature a skylight on the ceiling due to their position or the nature of the roof. Moreover, such kind of illumination is available only during the day. It is then necessary to use artificial lighting to obtain the same effect. Attention must be paid to the colour rendering, illumination level, (small) production of heat and total absence of radiations that can be dangerous for the paintings. Moreover, the lighting system is one of the plants with the highest fixed costs in an exhibition. For this reason, this service must be rationalised to lower as much as possible the power consumption. The paper has shown how a plant based on LED lamps can satisfy all these needs adding the flexibility related to the development of new technologies and light sources. To show the potentiality of this technology, the ‘red room’ of the Tosio Martinengo Art Gallery has been considered. First, the room was studied starting from the available pictures. Then the basic technical information about the luminaire used have been gathered on the field. A model based on DIALUX was then realised. Such model allowed to reconstruct the basic information about the lighting of the room. In particular, the illuminance is always aligned to the values suggested by literature and legislation. Finally, DIALUX can make an estimation of the fixed costs related to the lighting system, which resulted to be very low, especially in front of an optimal aesthetic performance.

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