ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA

SCUOLA DI INGEGNERIA E ARCHITETTURA

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

CORSO DI LAUREA IN INGEGNERIA EDILE-ARCHITETTURA

TESI DI LAUREA

in
Acustica applicata e illuminotecnica

LIGHTING of UNIVERSITY LECTURE HALLS:
a Design Proposal for Palazzo Malvezzi – Campeggi

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Anno Accademico 2019/20
Sessione I

Sommario

Molte aule universitarie a Bologna trovano spazio all'interno di edifici storici e palazzi nobiliari, non progettati a misura di studente in quanto costruiti per una diversa destinazione d'uso. L'apporto di luce diurna nelle stanze non è in genere sufficiente a soddisfare i requisiti per locali scolastici; inoltre l'illuminazione artificiale è realizzata in prevalenza con lampade a consumo eccessivo e di scarse prestazioni. In queste condizioni il visual comfort dello studente non risulta ottimale.
Il seguente lavoro di tesi si basa sull'analisi a cantiere aperto dello stato di fatto di alcune aule ad uso universitario e sulla loro riprogettazione a led. Il caso studio sono i locali di Palazzo Malvezzi-Campeggi a Bologna, tra cui i due grandi Saloni di rappresentanza al piano nobile e l'Aula Magna. E' stato possibile interagire con la componente acustica, qui non trattata, sviluppando una progettazione integrata in grado di soddisfare le esigenze di entrambe le parti. Le aule sono state qualificate mediante simulazioni con software di progettazione illuminotecnica, a norma EN 12464, analizzando il daylight factor e i parametri di visual comfort.

Abstract

Many university lecture halls in Bologna are based inside historic buildings and noble palaces, not designed for students as they are built for a different purpose. The daylight contribution in the rooms is usually not sufficient to satisfy the requirements for school premises; moreover, artificial lighting mainly consists in lamps with high consumption and low performances. Under these conditions the student's visual comfort is not optimal. The following work is based on the open site analysis about the state of art of some university classrooms and their led re-design. The case studies are the lecture halls of Palazzo Malvezzi-Campeggi in Bologna, including the two noble halls on the main floor and the Aula Magna. It has been possible to interact with the acoustic component, not treated here, developing an integrated project able to meet the needs of both parties. The classrooms were qualified through simulations with lighting design software, in accordance with EN 12464, analyzing the daylight factor and the visual comfort parameters.

Keywords:
Lighting; Visual comfort; Indoor Environmental Quality; Lecture halls; Learning performance; Learning environment; Cultural heritage constraints; Historical building; Historical constraints; Dialux; Energy efficienty; LENI; IEQ.

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Introduction

Lighting is a fundamental component for determining the quality of the indoor environment, especially for the educational buildings, where it represents an essential factor. Ensuring correct lighting increases user productivity and positively affects physiological and psychic factors in humans; light influences the perception of space and the well-being of those who occupy it. At the base of a lighting project there must always be a critical analysis of visual tasks, conditions and peculiarities of the environment.

To ensure the best possible visual performance for each specific task, it is necessary to refer to standards and recommendations that provide information regarding the amount of illuminance needed, the limitation of disturbances such as glare and all those fundamental factors for optimal comfort. The approach is not only quantitative but also qualitative: it is essential to identify the users of the space that has to be designed, the work activities and the architectural needs. A well-designed visual environment must support the activities that take place within it and contribute to the Indoor Environmental Quality. It will be necessary to analyze the spaces and their dimensions, the properties of the objects and surfaces, the users' positions and the duration of the visual task.

In new buildings, lighting can be designed by integrating the natural component in the best way, which improves user performance. However, in Italy the use of buildings of historical value is frequent for educational purposes; they are not designed for students, therefore the conditions of visual comfort are often inadequate. This work concerns the lighting analysis and redesign of nine lecture halls in Palazzo Malvezzi-Campeggi, seat of the Faculty of Law, in occasion of the opening of the restoration site.

After a presentation of the main concepts on the light phenomenon and the fundamental quantities for lighting technology defined in Chapter 1, the problem of user performance and the requirements are defined in Chapter 2 from a legislative point of view. The main reference for internal lighting is standard EN 12464-1, which provides the main verification parameters on visual tasks, including adequate lighting with its homogeneity in space

and the color rendering of the surfaces, as well as the correct balance of the luminous flux in order to increase visibility, and therefore communication, between users.
The lecture halls under study are valuable spaces to be restored subjected to architectural and cultural constraints, located in the historic center and used for university purposes. A careful on-site analysis was therefore carried out which allowed the subsequent creation of simulation models with Dialux certified software. Then in Chapter 3 the nine case studies are presented on the current state scenarios concerning artificial and natural lighting.
Thanks to the lighting software it was possible to analyze the case studies in the verification of the requirements necessary for an excellent visual performance for the activities provided in the lecture rooms. This made it possible to consider their critical issues and study various solutions so select the one that best suits the needs of the case.
Following the standards about visual comfort and users' well-being, a new LED lighting system was proposed in Chapter 4; it has been integrated with the acoustic component and other istances in order to achieve the needs of each part by improving space global comfort. This type of design consists in identifying the appropriate number, the right type, the best position and the management strategies of the luminaires through evaluations that consider every aspect based on the current standards and energy assessments.
A careful comparison between the ante-operam and post-operam lighting simulations is illustrated in Chapter 5, which also focuses on the energy evaluation of the new lighting design proposals. Increasing Indoor Environmental Quality also means improving the energy performance of buildings. In this chapter, following an energy analysis of the current and the design states, the benefits are assessed in terms of the LENI index (Lighting Energy Numeric Indicator), in accordance with EN 15193 and relamping interval.

Chapter 1

Light and lighting

1.1 The physical nature of light

Light is a form of electromagnetic radiation. To explain this effect there are two theories: Wave theory (Maxwell) and the Corpuscolar theory (Planck – Einstein). For the first one, light is an electromagnetic wave that travels with the same speed as $3 \cdot 10^8$ m/sec of electromagnetic waves (in a vacuum). Secondly, according to the corpuscular theory, light would be composed of a series of particles emitted by the light source, which move in the medium following the laws of classical mechanics [1]. Electromagnetic waves or photons will be discussed in this thesis. The representation of a classic electromagnetic wave is:

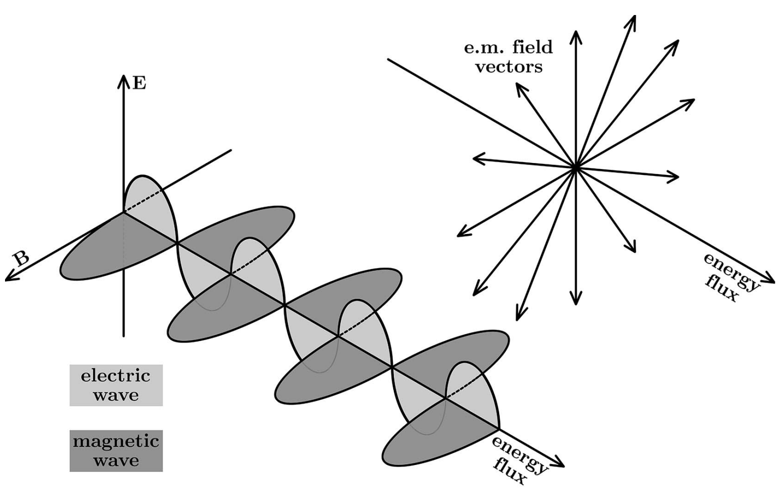


Figure 1.1: Electric wave and magnetic wave propagating in space vibrating on planes orthogonal to each other and orthogonal to the direction of propagation.

Light consists of an oscillating electric field and a magnetic field (variable over time) which proceed in a vacuum at a speed of $3 \cdot 10^8$ m/sec. Literature usually call *light* the portion of the electromagnetic spectrum between 380 nm and 780 nm, that is the area between the frequencies that are able to stimulate the human visual system: the visible spectrum [1]. The frequencies

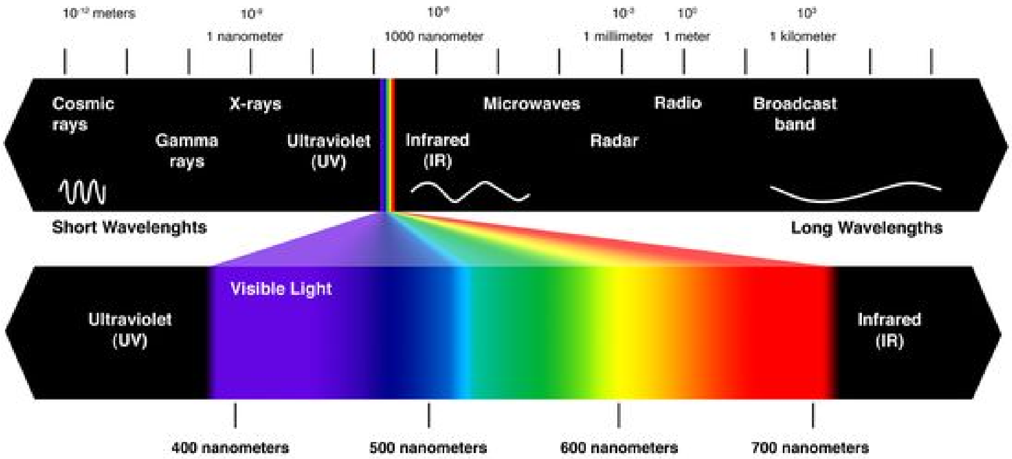


Figure 1.2: Electromagnetic spectrum for all the frequencies and all ther linked wavelengths. The range highlighted is made up of those wavelengths that can be perceived by human eye.

included in the mentioned range stimulate, with different efficacy according to the frequency, the receptors present inside the human eye, the cones and the rods, and allow vision. The relationship between the speed of light in a vacuum c, which is a universal constant, the wavelength λ and the frequency f is:

$$c = \lambda \cdot f \tag{1.1}$$

Taking into account also the medium in which the light propagates, indicating with n the refractive index of the medium and with v the actual speed of propagation of the light, the above relationship becomes:

$$v = \lambda \cdot f \cdot n \tag{1.2}$$

1.2 Notes on the human eye

Vision is linked to two types of receptors present in the human eye: *cones* and *rods*. The first are the photoreceptors responsible for color vision (*photopic vision*) and are mainly found in the fovea, the central part of the retina, through whose center passes the visual axis of the eye. The rods, on the other hand, are the photoreceptors responsible for low brightness vision (*scotopic vision*) and are found throughout the retina [1]. This one is the innermost

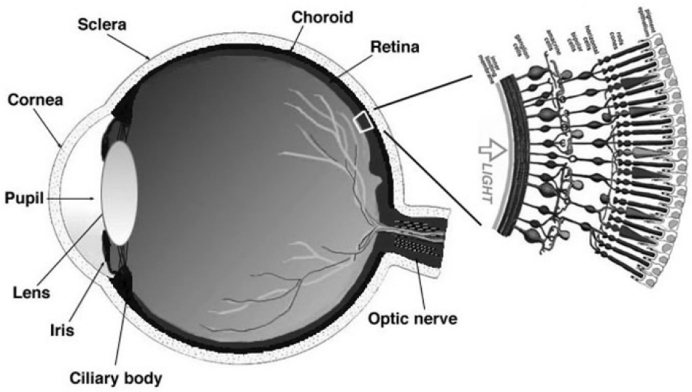


Figure 1.3: A drawing of a section through the human eye with a schematic enlargement of the retina.

membrane of the eyeball: it is a system of arteries, consisting of several layers, including one formed by the photoreceptors that transform the light signal into electrical impulses that then reach the brain through the optic nerve. Then the light signal enters through the pupil, which changes size thanks to the iris in order to let more or less light enter according to the quantity. Behind the iris there is the crystalline that is surrounded by the ciliary muscle, which makes it flatten or round according to the distance of the object, to convey the light on the retina and focus the image on it. To sum up, the first step is *adaptation*, which is the dimensional variation of the pupil to regulate the amount of incoming light, after that there is the *accommodation*, that is the dimensional variation of the lens to allow focusing, finally *convergence*, the synthesis of the two images by the brain in a single three-dimensional vision (*stereoscopic vision*) [1].

Humans have three classes of cones, one containing pigments sensitive to wavelengths related to blue (420 nm), a second sensitivity to wavelengths related to green (530 nm) and finally one with pigments sensitive to wavelengths related to red (565 nm). The combination of the three different curves ensures coverage of the visible spectrum. Having three different signals available depending on the frequency of the light received allows the perception of color. On the contrary, the rods are all of the same type and therefore perceive only the luminance levels in a colorless vision.

Of course, each of us has a different sensitivity and visual ability, therefore

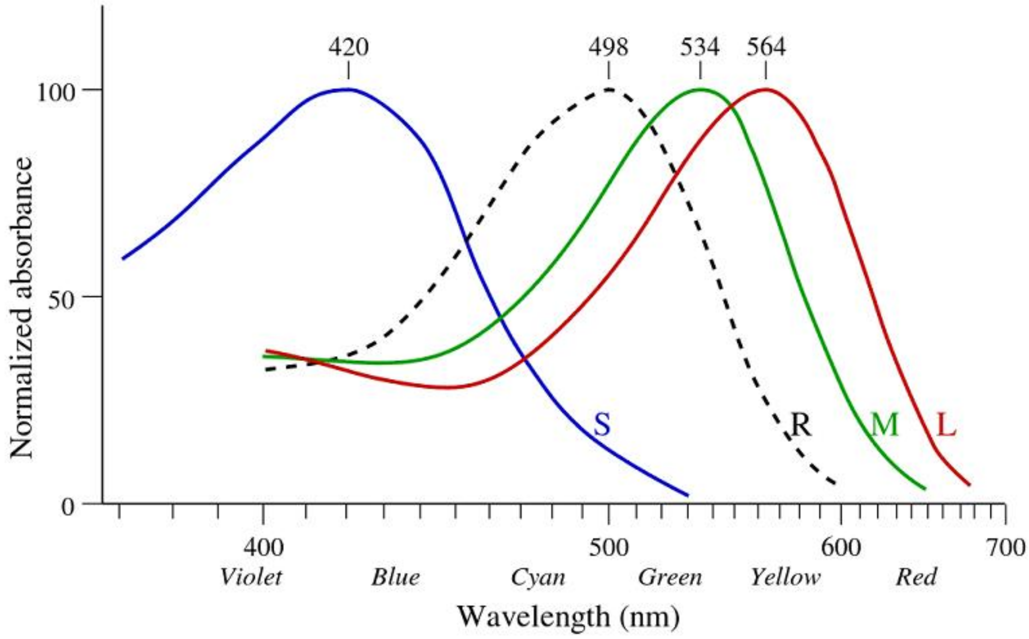


Figure 1.4: Sensibility curves of the three types of cones (blue, green and red curve) and rods (grey curve) at the different wavelengths of light.

it is necessary to refer to a shared model in order to generalize the results and give prescriptions of general validity. To quantify the visual sensitivity of the average human eye to radiation of different wavelengths but of equal energy, a function called *visibility factor* $K(\lambda)$ is used, the value of which depends on λ. $K(\lambda)$ is defined in such a way that given two radiative powers $P(\lambda_1)$ and $P(\lambda_2)$ relating to two monochromatic radiations of different λ, the visual sensations generated by them are equivalent if it occurs that:

$$P(\lambda_1) \cdot K(\lambda_1) = P(\lambda_2) \cdot K(\lambda_2) \tag{1.3}$$

The visual sensation does not depend on the amount of radiant energy that affects the retina, but on the incident power and the wavelength. The visible spectrum ranges from $\lambda = 380\text{nm} \div 780\text{nm}$ and the maximum sensitivity is obtained for $\lambda = 550\text{nm}$. Moving towards the extremes of the visual field it is necessary to increase the power of radiation to obtain the same visual sensation. The power emitted for each individual wavelength must be weighed according to the sensitivity of the eye at that wavelength. For this purpose, the response of the eye to radiation of various wavelengths has been studied both in daylight conditions (photopic vision) and in conditions of lower light intensity (scotopic vision).

The CIE (*Commission internationale de l'éclairage*) has codified an eye with an average sensitivity, the result of a statistical elaboration carried out on a large number of subjects. The observer will perceive the light at $\lambda = 550$ nm as more intense, where the eye therefore has maximum sensitivity, while it will gradually estimate the light with greater or lesser λ intensity. Moving towards the two lower limits of the visible spectrum, to obtain a feeling of equivalence of the two light beams, it will be necessary to increase the power of the radiation. For $\lambda < 380$ nm and for $\lambda > 780$ nm there will be no visual perception. Identifying the multiplicative constant in $K(\lambda)$ with the maximum value K_{max}, a relative spectral visibility coefficient is defined:

$$V(\lambda) = \frac{K(\lambda)}{K_{max}} \qquad 0 < V(\lambda) < 1 \tag{1.4}$$

The *relative visibility curve* can be considered as the ratio between effects produced by radiation of a given wavelength compared to that of maximum sensitivity. It is obtained from cones' data and it has a peak corresponding to the yellow/green wavelengths.

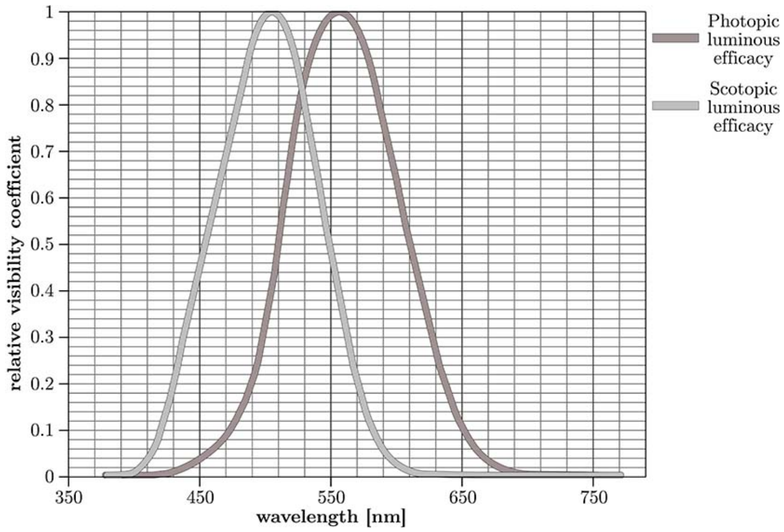


Figure 1.5: Purkinje effect: The change in the sensitivity of the eye colors, which occurs from sunny hours to those characterized by low light. In practice, we switch from photopic to scotopic vision and the visibility curve shifts to the left, with the peak corresponding to $\lambda = 507$ nm, typical of blue.

1.3 Photometric quantities

1.3.1 Luminous flux

After investigating the physiology of the eye, the fundamental quantities of lighting technology are exposed here; recommendations and requirements took in consideration for this work are provided by normative, specifically the EN 12665 [2].

Luminous flux (Φ) is the sum of the products of the power carried by the electromagnetic radiation for each wavelength for the corresponding relative visibility value; it is used to describe how much light comes out of a light source (fig. 1.6). In mathematical terms:

$$\Phi = K_{max} \int_{380nm}^{780nm} V(\lambda) \frac{dP(\lambda)}{d\lambda} \, d\lambda \qquad (lm) \tag{1.5}$$

Where:

- Φ is the luminous flux, in lumen;
- K_{max} is the sensitivity of the human eye relative to the λ of maximum sensitivity: in photopic vision ($\lambda = 555$ nm), K_{max} corresponds to 683 lm/W;
- $P(\lambda)$ is the radiant power at a certain λ;
- $V(\lambda)$ is the relative spectral visibility coefficient at a certain λ;
- λ is the wavelength, in nm.

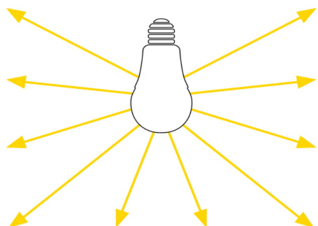


Figure 1.6: Luminous flux [Φ] = [lumen] = [lm] = [cd $\cdot$ sr].

1.3.2 Luminous intensity

The *luminous intensity* (I_ω) describes how the luminous flux varies with respect to the angular direction of light output from a source (fig. 1.7):

$$I_\omega = \frac{d\Phi}{d\omega} \qquad (cd) \tag{1.6}$$

Where:

- I_ω is the light intensity, in candela;
- Φ is the luminous flux, in lumen;
- ω is the solid angle, in steradians.

The light intensity is measured in candela (cd): given a certain direction (one steradian), one candela corresponds to the luminous intensity of a light bulb of one lumen. In particular, one candela is the luminous intensity emitted in a given direction by a given source that emits a monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz ($\lambda = 555$ nm) with an energy intensity in that direction equal to 1/683 W/sr.

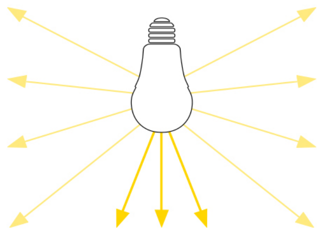


Figure 1.7: Luminous intensity $[I_\omega]$ = [candela] = [cd].

1.3.3 Illuminance

Illuminance (E) on a surface produced by a source is the relationship between the flux coming from the source and the surface itself (fig. 1.8). If the source is point-like, the flow is contained in a solid angle centered on the source; by increasingly narrowing the surface until it collapses in one point the illumination produced by a point source on a point of a surface is obtained.

$$E = \frac{d\Phi}{dS_{ric}} \qquad (lx) \tag{1.7}$$

Where:

- E is the illuminance, in lux;
- Φ is the luminous flux, in lumen;
- dS_{ric} is the area irradiated, in m^2.

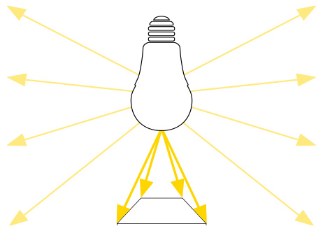


Figure 1.8: Illuminance $[E] = [\text{lux}] = [\text{lx}] = [\frac{lm}{m^2}]$.

1.3.4 Luminance

Luminance represents the visual sensation perceived by the human eye if hit by the light directly produced by a light source or reflected by a surface (fig. 1.9); is given by the relationship between the light intensity emitted, reflected or transmitted from the surface according to the direction of observation and the effective emission area of the surface itself.

$$L_\omega = \frac{d\Phi}{(dS_{em} \cdot cos\Theta) \cdot d\omega} = \frac{dI_\omega}{dS_{em} \cdot cos\Theta} \qquad (nt) \qquad (1.8)$$

Where:

- L_ω is the luminance, in nit;
- Φ is the luminous flux, in lumen;
- I_ω is the light intensity, in candela;
- ω is the solid angle, in steradians;
- $(dS_{em} \cdot cos\Theta)$ is the effective emission area, in m^2.

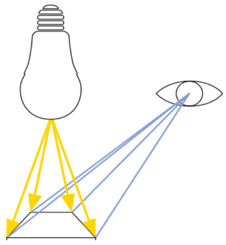


Figure 1.9: Luminance $[L_w] = [\frac{cd}{m^2}] = [\text{nit}] = [\text{nt}]$.

The luminance depends on the position of the observer. If the observer moves he will be reached by an intensity different from that which reached him in the previous position and will see the emitting surface under a different angle: therefore overall the luminance perceived by the observer will change.

Measure	Symbol	Unit
Luminous flux	Φ	[lumen] = [lm]
Light intensity	I_ω	[candela] = [cd]
Illuminance	E	[lux] = [lx]
Luminance	L_ω	[nit] = [nt]

Table 1.1: Summary table of photometric quantities.

1.4 The fundamental laws of lighting

Each point of a light source must be considered a source of spherical waves with a center at that point, with a wavefront area that increases proportionally to the square of the distance from the source during the propagation. Since the energy emitted is uniformly distributed on the spherical surface, it can be said: the intensity of the light radiated by a point light source is inversely proportional to the square of the distance from the light source itself (*law of the square of the distances*).

Since the direction of propagation is always perpendicular to the wavefront, a surface element however oriented receives energy as a function of the projection of that element in the direction of propagation. It follows that the energy that passes through a surface element is proportional to the cosine of the angle between the normal to the surface element and the direction of propagation (*cosine law*).

An immediate application of the above laws allows to calculate the illuminance E on a surface element dA due to a point light source P with light intensity I_Θ (fig. 1.10):

$$E = \frac{d\Phi}{dS_{ric}} = \frac{I_\omega \cdot d\omega}{dS_{ric}} = \frac{I_\Theta}{dS_{ric}} \cdot \frac{dS_{ric} \cdot cos\Theta}{r^2} = \frac{I_\omega}{r^2} \cdot cos\Theta \qquad (1.9)$$

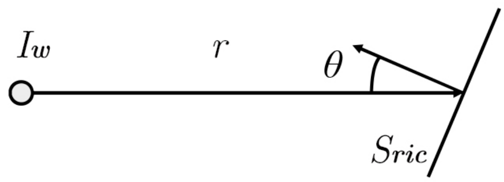


Figure 1.10: Relationship between illuminance and light intensity.

If a point surface element dS_{em} emits light radiation in all directions with light intensity equal to: $dI_\omega = dI_0 \cdot cos\Theta$ where I_0 is the luminous intensity emitted perpendicularly to dS_{em}, the luminance L_0 of the area element dS_{em} is independent from the direction of observation and holds:

$$L_0 = \frac{dI_0}{dS_{em}} \qquad (1.10)$$

Calling *lambertian* a reflective or emitting surface with uniform luminance independently of the direction of view, it can be said that the light intensity emitted by a surface of this type in the direction Θ is proportional to the intensity in the perpendicular direction (I_0) according to the cosine of the angle Θ between the two directions (*Lambert's law*).
The radiation leaving dS_{ric} can be produced by emission from a light source but also by transmission or diffusion by an illuminated surface. In this second case, if E is the illuminance on dS_{ric} caused by a light beam coming from any direction and if the luminous intensity emitted by that surface behaves as mentioned above, the luminance L of the element dS_{ric} is equal to :

$$L = \frac{\rho \cdot E}{\pi} \qquad (1.11)$$

where ρ is the reflection factor of that surface.

1.5 Light sources and lighting equipment

The artificial sources are composed of two parts: the lamp and the lighting fixture. The first converts electrical energy into luminous flux, the second distributes the luminous flux in the desired way. The range of lamps is particularly rich and varied, which makes the task of selecting the most suitable types for a given application undoubtedly difficult. The best way to obtain the most suitable solution is to carefully examine the characteristics and performance of each lamp until finding the suitable model.
However, light sources can be classified into only three main categories (fig. 1.11): radiation by thermal effect (incandescent lamps), discharge in gases and vapors (fluorescent lamps, mercury or sodium vapors, etc.) and photon emission (LED). Unlike LEDs which, given the strong development underway, cannot yet be rigorously classified, traditional incandescent and discharge lamps are consolidated and schematized technologies.

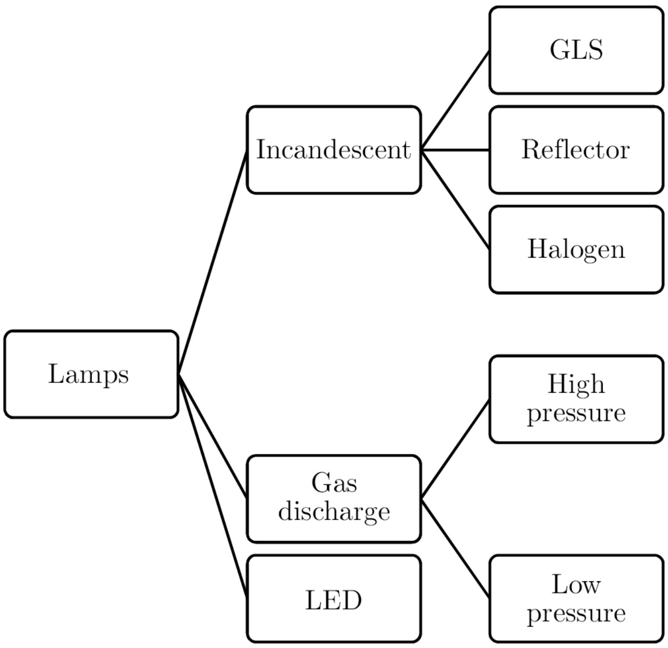


Figure 1.11: Scheme of traditional light sources.

Nowadays conventional lamps are now used almost only as a reserve, yet there is no lack of reason to continue to adopt the most efficient. However, LEDs are ramping up in all applications by virtue of their enormous luminous efficiency and their very long life. It is therefore the responsibility of the designer to choose the most suitable light source for each application. Essentially the parameters of the lamps are defined by the following:

– Luminous flux Φ, in lumen;

– Specific or luminous efficiency η, in lm/W;

– Dimension and shape;

– Start-restart times;

– Color temperature;

  Warm, $T_{CP} < 3300$ K;

  Neutral, $3300 < T_{CP} < 3300$ K;

  Cool, $T_{CP} > 5300$ K.

– Color rendering index R_a (0 – 100);

– Duration.

	W	lumen	lm/W	R_a	Hours
Incandescent	15 – 150	90 – 2 220	12	100	1 000
Halogen	10 – 150	140 – 3 200	22	100	2 000
Fluorescent	24 – 58	1 750 – 5 200	90	90	12 000
Compact fluorescent	5 – 55	250 – 4 800	80	90	10 000
Metal halide	20 – 400	1 650 – 35 000	90	90	10 000
High pressure sodium vapor	50 – 400	5 000 – 60 000	150	40	15 000
LED	0.1 – 5	2 – 250	50	90	50 000

Table 1.2: Comparison between the main characteristics of light sources [12].

Luminaires have the task of distributing the flux emitted by the lamps in an appropriate way exploiting the optical properties of reflection, refraction and transmission (transparency); they also protect light sources from external agents, mainly shocks, solid bodies (dust) and liquids (water). In particular, they are characterized by the luminous efficiency, η, in lm/W, as the ratio between the luminous flux of the luminaire and that of the lamp:

$$\eta = \frac{\Phi_{luminaire}}{\Phi_{lamp}} \tag{1.12}$$

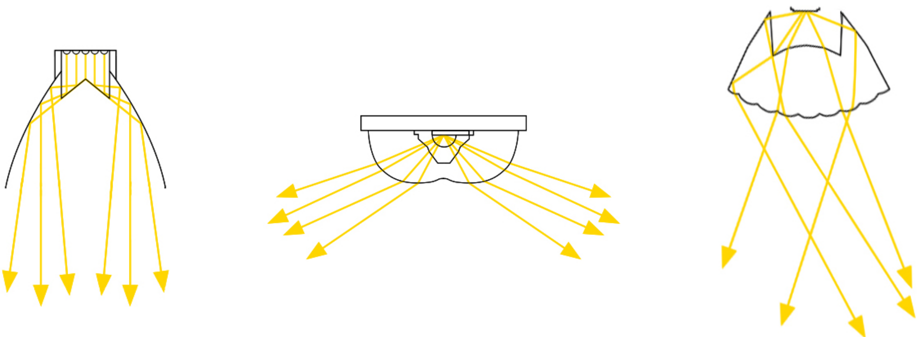
This means that not all the flux emitted by the sources affects the reference plane: part of it is absorbed by the internal surfaces of the lighting fixture. A portion of the flow leaving the latter is still directed outside the visual task and absorbed by the walls or other surfaces of the environment. The first contribution to losses therefore depends on the layout of the optics of the device and the materials used in them.

The losses that occur on the flux leaving the lighting fixture are normally quantified by a coefficient called utility (U) which takes into account the reflection factors of the environment and its geometry and the position of the source [12]. Optical efficiency η and utility U determine the useful percentage of the generated flow which contributes, under ordinary conditions, to creating the required illumination on the visual task. Their product defines in particular the so-called UF utilization factor of the system:

$$UF = \eta \cdot U \tag{1.13}$$

The utilization factor is generally provided by the lighting fixture manufacturer who, taking into account the optical performance, provides the UF in specific tables referring to specific geometries of the room and installation and to specific environment reflection coefficients.

To direct the light, the luminaires exploit the phenomena of reflection, refraction and diffusion and are respectively indicated as (fig. 1.12):



(a) Reflectors luminaires direct the light emitted by the light sources in specific directions.

(b) Refractors luminaires are made up of a transparent material casing which diffuses light radiation by refraction.

(c) Diffusing luminaires emit light by uniforming the luminance in the various directions.

Figure 1.12: Luminaires typologies.

The luminaires can be chosen by observing the photometric curves provided by the manufacturers: these curves represents the direction and intensity of the light emitted by the source and they can be associated with any object that emits light [1]. These curves are represented in the form of polar diagrams, that are graphs shown on a portion of the plane, with a center (the origin), and a reference axis starting from the center. Any point of the plane can be identified simply by indicating the angle with respect to the reference axis and the distance from the origin (fig. 1.13). By representing the light intensity, measured in a certain direction, with a segment of length proportional to it and coming out from the source or from the device, a closed surface is obtained which is the place of the extremes of the infinite segments; the volume enclosed by this surface is called photometric solid.

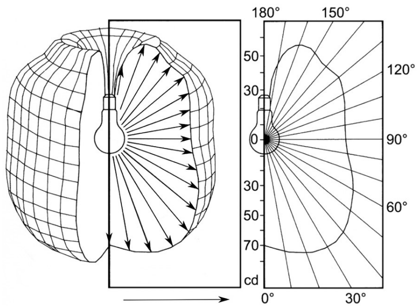
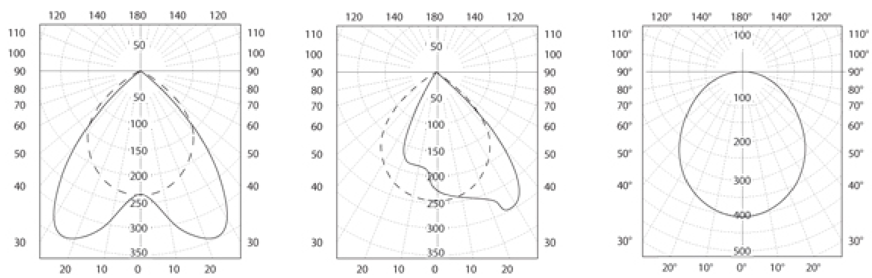


Figure 1.13: Representation of photometric solid: photometric curves are obtained by intersecting the solid with planes through the optical axis.

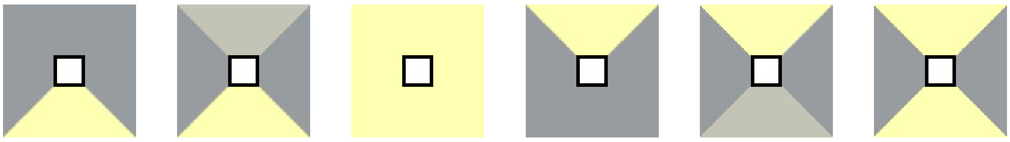
Thanks to the photometric curves it is possible to differenciate the luminous emission of the luminaires in symmetric, asymmetric and rotationally symmetric (fig. 1.14):



(a) Symmetric emission. (b) Asymmetric emission. (c) Rotationally symmetric emission.

Figure 1.14: Luminous emission perpendicular to the lamp longitudinal axis (solid line) and in the longitudinal direction (dotted line).

The International Lighting Commission (CIE) has also classified the lighting fixtures according to the distribution of the luminous flux, dividing them into emission categories (fig. 1.15):



(a) Direct. (b) Semi direct. (c) Diffused. (d) Indirect. (e) Semi indirect. (f) Direct indirect.

Figure 1.15: Total flux distribution according to CIE classification.

Another feature of the luminaires is the opening of the beam, which can be narrow, medium or wide. It describes how concentrated is the beam of light produced: it is the angle within which the intensity is reduced to 50% of its maximum generally measured along the axis (fig. 1.16).

Figure 1.16: Light beam opening: the less the angle of emission is acute, the less the light beam will be concentrated and the emission will become more diffused.

The main photometric parameters of a luminaire are:

- luminous flux Φ, in lumen;
- luminous efficiency η, in lm/W;
- color temperature and rendering index R_a;
- total flux distribution (direct, indirect, etc.);
- opening of the light beam: narrow medium or wide;
- light emission: symmetric, asymmetric, rotationally symmetric;
- start-restart times and duration.

Chapter 2

School buildings lighting

2.1 Light and visual comfort

Visual comfort is the condition of well-being and satisfaction of visual needs during the performance of activities. This element is important as students continuously adapt their vision, focusing on the lighting of horizontal and vertical planes; it therefore becomes essential to ensure correct lighting to avoid eyestrain and increase productivity. Visual comfort in classrooms is a crucial factor for learning [13]; the absence of good environmental comfort can influence students' learning ability wherease a comfortable environment increases their productivity [14]. Today lighting designers, following the standards, perform simulations to predict lighting on horizontal planes, but this only allows viewing. Instead, it is also important to evaluate illuminance at eye level together with the distribution of the spectral power of light to stimulate the circadian system [15].
Visual comfort can be obtained by integrating natural light with artificial light, also considering the psychological effects that follow; the level of visual comfort cannot be assessed objectively but there are several factors that influence visual performance [16].

Illuminance must ensure that a surface is correctly illuminated; is the ratio between the luminous flux and the area of the surface on which it affects [3]. The standard establishes minimum and average values to avoid visual fatigue, in relation to the type of activity expected in a given environment, and these values are influenced by objective factors, such as the absorption and reflection of the luminous flux of the materials, and from subjective factors depending on user's visual abilities and physical condition.

Light distribution is an important factor because it determines the specific lighting conditions in the task area with respect to the surrounding environment: too high contrasts can favor a discomfort situation.

The *glare* phenomenon is caused by excessive luminance contrasts or by the saturation of the visual system, that is when the light beam is oriented towards the eyes and is located at a close distance from them (fig. 2.1, 2.2). This phenomenon reduces performance by preventing normal activities (debilitating glare) or leads to a feeling of discomfort causing strain on the eyesight (disturbing glare). The CIE has developed the UGR factor to evaluate glare in every field of application. Research conducted by the Catholic University of Louvain has shown that glare and the consequent perception of discomfort are also significantly influenced by other factors, physiological, psychological or contextual [17].
The potential factors that influence the perception of discomfort are factors related to light (luminance, contrast effect, size and position of the glare source...), subjective factors (gender, age, sensitivity to glare, pigment of the iris, illumination of the previous environment, psychic state...) and context factors (light spectrum, light direction...).

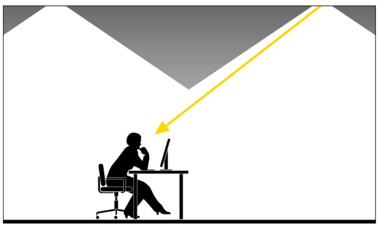


Figure 2.1: Direct glare.

Causes
Unshielded lighting fixtures Surfaces with strong brilliance
Effects
Drop in concentration Increase in the margin of error Fatigue

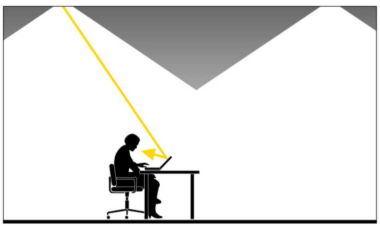


Figure 2.2: Reflected glare.

Causes
Reflective surfaces Badly positioned appliances Badly positioned jobs
Effects
Drop in concentration Increase in the margin of error Tiredness

The *perception of color* is assessed to ensure a reliable restitution of surfaces' colors but also for the psychological influence caused especially in closed places. Two factors are used: the color temperature and the color rendering index. There are numerous researches on the influence of colors on the psyche, in particular in schools and offices the advantages of cold and warm lights are being analyzed. The color temperature influences the state of sleepiness: compared to 5000 K, a temperature of 3000 K slows down the central nervous system [18].

2.2 Non-visual effects of light

In addition to visual comfort, light has defined non-visual effects on humans, which affect biological functions such as mood, alertness and sleep quality [3]. Cones and rods have little influence on the circadian system [19], on the other hand other photoreceptors act on it, the ganglion cells containing melanopsin, a protein that acts as a sensor of light changes and which is able to measure the incident light intensity and therefore to understand if it is day or night [20]. On this type of photoreceptors depend the so-called NIF effects (non-image forming or non-visual effects) [21] which have an important impact on human biological functions and the consequent psychophysiological well-being. Because of their peculiarities, ganglion cells are not able to guarantee the functions of creating "visual" images but thanks to the constancy in the response they guarantee an understanding of daylighting levels of the surrounding environment. In fact, ganglion cells take part in the mediation of various non-formation processes of the image, reflecting it at a subconscious level. For these reasons, the light response of these photoreceptors is defined as a non-visual or non-formation response of the image; this response includes a wide variety of reactions, of which the most influential is certainly that of regulating the circadian endogenous clock.
While the visual information, through cones and rods, are sent to the visual cortex as electro-chemical signals, the light, through the NIF ways, is transmitted to the Suprachiasmatic Nucleus (SCN) and to regions of the brain, such as the pineal gland, responsible for the synthesis of melatonin, the sleep hormone.
To optimize the lighting conditions of the indoor environment, correlations with other physical properties are also being studied: according to Revell et al, non-visual effects depend on the spectral distribution of the light signal, on the intensity and also on the duration of exposure [22].
The analysis of the quality of light in closed environments must therefore include both the assessment of the non-visual effects of light and compliance with regulatory requirements[23][24].

2.2.1 Circadian rhythms

With circadian rhythm literature defines the synchronization of the biological clock that defines humans daily rhythms such as sleep and wakefulness but also functions such as alertness, concentration and body temperature.
Light is the main factor for the regularization of the biological clock, in the absence of its stimulation, the sleep-wake cycle is synchronized with respect to the alternation of light and darkness, influencing the general state of health and human behavior.
The secretion of melatonin, the sleep hormone, follows a certain trend over 24 hours: the maximum levels occur during the night, during the day the levels decrease considerably as the light causes its suppression. Melatonin affects several behavioral aspects: its absence increases the level of alertness, its presence promotes relaxation. In schools, artificial lighting does not exceed 1000 lux on the work surface (usually reaches much lower values) while the external illumination varies between 2000 and 10 000 lux at ground level. It follows that the majority of the closed rooms have too low illuminance values to keep the circadian clock synchronized and therefore inhibit melatonin secretion; there is biological darkness even during the daytime [25].

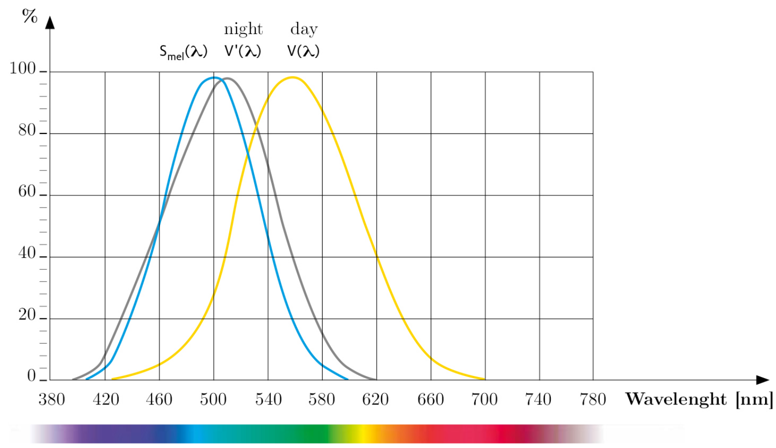


Figure 2.3: Relative spectral sensitivity and melanopic effect: $V(\lambda)$ = sensitivity to light, daytime view with cones; $V'(\lambda)$ = night view with rods; $S_{mel}(\lambda)$ = suppression of melatonin with photosensitive ganglion cells.

Light presence, natural and artificial, is instinctively related to the state of alertness, which coincides with the suppression of melatonin during daytime. Similarly, good sleep quality (which, in case of schools, improves teaching performance) is affected by the exposure of light during the evening. Intense light can phase out the circadian rhythm and delay sleep. These effects, which are certainly subjective, depend on the light intensity, the duration of exposure and the spectral composition, but also on other factors such as gender and age. Several studies have revealed that subjects of a young age are more sensitive than older subjects at short wavelengths (460nm, the spectrum that influences circadian reactions) perhaps for reasons related to the worsening of the crystalline lens over the years . Exposure to light at different times of the day causes advances or delays in the circadian phase and the direction and extent of these phase shifts depend on the moment in which the light stimulation takes place [26]. Considering the circadian sensitivity curve, the reactions related to melanopsin are perceivable at different wavelengths compared to the wavelength of the photopic vision, for example the blue wavelengths, barely perceptible by the human eye, have a large importance for melatonin suppression. So a light source in the yellow-red field has a good color rendering and good visual function but does not collaborate in the suppression of melatonin [25]. For a more complete lighting design, it is necessary to evaluate not the lighting levels but also the spectral distribution of the light.

2.3 Lighting influence on user performance

Since students spend a lot of time indoors, even with optimal natural lighting, integration with artificial light is a fundamental requirement. Just think of the continuous variation of the incident solar radiation and, in school buildings, of all those particular activities whose performance is satisfied only with the aid of luminaires. The connection between light and well-being is an essential element and considering the continuous exposure of students to light, it's possible to optimize the performance of the activities by stimulating circadian reactions. The variation of the light spectrum affects the level of alertness, heart rate and body temperature; at short wavelengths (460 nm) the level of melatonin in the blood decreases and body temperature and heart rate increase, therefore alertness and physical and mental productivity [23], [27] and [28]. Numerous studies have been conducted to evaluate how intensity and color temperature affect students' performance. Studies conducted on university students during lessons in lecture rooms subjected to different color temperatures, 4000 K and 17000 K, have allowed us to observe how exposure to a very high color temperature helped students to maintain a high level of vigilance [29].

Natural lighting is a fundamental resource for improving the quality of the indoor environment; in particular, numerous researches have been carried out and they reveal the positive effects in school architecture. Since the 1970s, a study conducted by Collins focused on the presence of transparent

surfaces in classrooms showed that the presence of natural lighting plays a key role in the quality of the spaces. The various reasons have been verified in subsequent studies, which analyze the relationship between lighting and well–being, as well as their influence on student performance [30].
In 1992, in Sweden, four classes were analyzed: two in which natural lighting was present, two without; two in which there was warm artificial lighting (3000K), two in which it was cold (5500K). Thanks to the results, it was understood that there is a correlation between the lighting levels and the well–being of the students, advising against the use of classrooms without windows [31].
In the same context, in 2002, a study conducted for ENEA carried out an analysis to evaluate the influence of the light environment on the user, by carrying out two tests. The first was created inside a cabin in which there was only the contribution of artificial lighting, in the second it was possible to control natural light through sunscreen blades. To the seven interested subjects were shown different images (negative, neutral and positive, based on the presumed emotional stimulus they would have provided), and the different reactions were recorded in both tests [25]. The results showed that the reactions vary more influentially with the variation of the environmental condition rather than the type of stimulus correlated to the images. Also in this case, the research wants to act as a starting point for further experiments on the role of indoor lighting on human well–being. It has now become evident how various factors, especially subjective ones, related to the perception of light affect the consideration of the environment itself.
The preference of users becomes another factor to be taken into consideration, as it directly affects the perception of well–being. Galasiu and Veitch, for example, in 2006 verified through interviews with students and workers that 65% and 78% respectively prefer natural lighting over artificial lighting, both for psychological and production reasons [32]. In 1992, Kuller and Lindsten [31] found that the contribution of natural light was extremely significant to allow students to achieve the goals set by teachers; the same conclusion was confirmed by an American research conducted in the 2000s by Hescong [33].
The information collected in these researches, still being analyzed today, despite being a source for understanding the phenomenon of natural lighting in indoor environments, does not exhaust the subject. Surely these studies confirm an increase in interest on the theme, with the aim of meeting the individual's needs, both psychological and performance. In the same way, there are technical reasons (the fulfillment of the regulations in force) and economic (focused on energy saving) to be taken into consideration for the evaluation of natural lighting.

2.4 Legal requirements

2.4.1 Indoor artificial lighting

About light and lighting, EN 12665 defines the basic terms and definitions and specifies which parameters to consider when determining lighting requirements [2]. However, the main document for interior lighting is EN 12464 which defines precise quantitative thresholds for different types of activities [3]; the standard specifies lighting requirements for indoor workplaces, which correspond to the needs of visual comfort and visual performance.

The main parameters that characterize the light environment are:

– luminance distribution;

– illuminance;

– direction of light, lighting in the interior space;

– colour rendering index and colour appearance of the light;

– variability of light (levels and colour of light);

– glare.

The standard establishes three different types of areas in a workplace [3]:

– Task area: It's the surface where all the elements that participate in the observer's visual task fall.;

– Surrounding area: It's a band at least 0.5 m wide surrounding the task area within the visual field;

– Background area: It's a band of at least 3 m around the surrounding area, contained in the limits of the space considered.

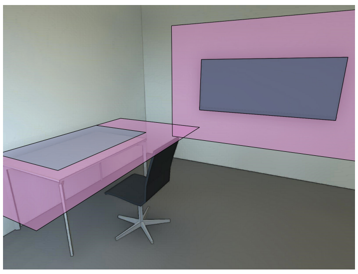


Figure 2.4: Task areas and Surrounding areas according to EN 12464-1.

Minimum or maximum values to be respected for illuminance and its uniformity, discomfort glare and colour rendering index are given in Tab. 2.5.

Luminance distribution: To obtain a correct balance, excessive luminances that cause glare, too high luminance contrasts that cause fatigue and too low luminances and contrasts that make the working environment uninspiring must be avoided. In addition to lamps' direct luminance, the indirect portion due to the light reflected from the surfaces must be taken into consideration: a surface reflects light differently depending on the its reflection coefficient that is a function of the color and material of the surface. Recommended reflectances for the major interior diffusely reflecting surfaces are (Tab.2.1):

Surface	from	to
Ceiling	0.7	0.9
Walls	0.5	0.8
Floor	0.2	0.4
Furniture	0.2	0.7

Table 2.1: Recommended reflection coefficients for some surfaces.

Illuminance: Illuminance and its distribution over the task area and the surrounding area greatly influence the perception of the visual task.
Lighting values in Tab. 2.5 are maintained illuminances on the task area and they can be horizontal, vertical or inclined. The average illuminance for each task must not fall below the value indicated in Tab. 2.5, regardless of the age and conditions of the installation. To give a perceptual difference, according to EN 12665 [2], the recommended steps of illuminance are: 20 – 30 – 50 – 75 – 100 – 150 – 200 – 300 – 500 – 750 – 1 000 – 1 500 – 2 000 – 3 000 – 5 000 [lux]. The illuminance can be increased or decreased by at least one step on the illuminance scale if the visual conditions differ from those assumed as normal: manteined illuminance should be increased when visual work is critical, the details of the activity are unusually small or low contrast and the activity is carried out for an unusually long time.
To create a well balanced light distribution, the illuminances of all surfaces must be taken into consideration; in particular in all closed environments used for offices, health or education the maintained illuminances on the main surfaces must have the following values:

- $E_m > 75$ lx with $U_0 \geq 0.10$ on the walls;
- $E_m > 50$ lx with $U_0 \geq 0.10$ on the ceiling.

Because the large spatial variations of the illuminances in the activity area can cause visual stress and discomfort, once the illuminance is established for a certain area, the illuminance level in the surrounding area can be lower but must still respect constraints (Tab.2.2):

Illuminance on the task area E_{task} (lux)	Illuminance on immediate surrounding areas (lux)
≥750	500
500	300
300	200
200	150
150	E_{task}
100	E_{task}
≤50	E_{task}

Table 2.2: Relationship of illuminances on immediate surrounding to the illuminance on the task area. The background area shall be illuminated with a maintained illuminance of 1/3 of the value of the immediate surrounding area

For lighting from artificial lighting the illuminance uniformity in the immediate surrounding area shall be $U_0 \geq 0.40$ while on the background area it shall be $U_0 \geq 0.10$, where U_0 is defined as E_{min}/E_m. On the other hand, in the case of window lighting, the available daylight decreases rapidly with distance; the additional benefits of daylight can compensate for the lack of uniformity.

Glare: it can be annoying, if it causes fatigue (discomfort glare), or debilitating if it prevents the correct execution of the task (disability glare), and is caused by unsuitable point values or luminance gradients. The discomfort glare produced by the luminaires is identified by the *UGR* (*Unified Glare Rating*), a parameter that can be assessed through tables provided by the manufacturers of the fixtures: it ranges from 10 (no discomfort) to 30 (maximum undesired effect).
According to UNI 10380, the evaluation scale is made up of categories named with letters, from *A*, which is the most strict condition, to *E*, with reference to the luminance limit curves [6]:

- A: Very difficult visual task;

- B: Visual task requiring high visual performance;

- C: Visual task requiring normal visual performance;
- D: Visual task that requires modest visual performance;
- E: For interiors where people are not located in a specific workplace but move from place to place, performing tasks that require modest visual performance.

To evaluate the discomfort glare caused by daylight, that is from windows, there is no standardized method; instead as regards the glare caused by artificial lighting, the CIE tabular method is used, based on the following formula:

$$UGR = 8\log_{10}\left(\frac{0.25}{L_B}\sum\frac{L^2\omega}{p^2}\right) \tag{2.1}$$

Where:

- L_B is the background luminance, in cd/m^2;
- L is the luminance of luminaire, in cd/m^2;
- ω is the solid angle of view of the luminaire, in sr;
- p is the Guth index of the observer's position with respect to the source.

To reduce veiling reflections and reflected glare, which can alter the visibility of the visual task, it is good to use the following expedient: arrange the workstations with respect to lighting fixtures and windows, use opaque finishing surfaces, limit the luminance of the fixtures and windows and design bright walls.

Lighting in the interior space: In addition to the lighting of the tasks, the volume of space occupied by people should be illuminated, in order to highlight objects and surfaces texture and improve the visibility of people in the space, allowing good communication and the recognition of what surrounds people inside the illuminated space. This is obtained by providing adequate average cylindrical illumination, E_z, in space: $E_z \geq 50$ lux (for teaching area 150 lux are better) with $U_0 \geq 0.10$, on a horizontal plane at a specified height, for example 1,2 m for sitting people and 1,6 m for standing people above the floor.

To optimize the general appearance of an interior, the balance between diffused and direct light should be taken into consideration. Lighting should not be too directional, as it would produce hard shadows, but not too diffuse as the environment would be too bright and boring. In addition, multiple shadows caused by directional lighting from multiple positions should be avoided as they may cause a confusing visual effect. A good indicator for a correct modeling of interior spaces is the ratio between cylindrical and horizontal illuminance in a point, with a value between 0.30 and 0.60:

$$0.30 \leq \frac{E_z}{E_o} \leq 0.60 \tag{2.2}$$

Color aspects: Regarding these aspects, we refer to two attributes which are to be considered separately:

- the colour appearance of the light;
- its color rendering capabilities, which affect the color appearance of objects and people.

The colour appearance of the lamp is quantified by its correlated colour temperature, T_{CP}, distinguished in warm (yellowish-red), neutral and cool (bluish-white), and its choice depends on practical, aesthetic and psychological factors.

Colour appearance	T_{CP} [K]
Warm	below 3 300
Intermediate	3 300 to 5 300
Cool	above 5 300

Table 2.3: Color classification of light according to EN 12464-1 [3].

The color rendering index (R_a) is instead an indicator of the visual quality of a light source, linked to its ability to make people and objects appear with colors as natural as possible. According to UNI 10380, lamps are divided into five groups, from 1A, 1B to 4, from an excellent R_a to a poor one; the maximum value is 100, which corresponds to perfect graphic rendering [6]:

- $1A$ corresponds to $R_a > 90$;
- $1B$, corresponds to $80 < R_a < 90$;
- 2, corresponds to $60 < R_a < 80$;
- 3, corresponds to $40 < R_a < 60$;
- 4, corresponds to $20 < R_a < 40$.

To guarantee the necessary illumination over time, the lighting design provides for the calculation of the maintenance factor (MF) which evaluates the decay of the luminous flux of a lighting system.
The designer should indicate the MF and list all the assumptions made in the derivation of the value, specify the lighting equipment suitable for the application environment and prepare a complete maintenance program that includes the frequency of lamp replacement, the appliance, the room and window cleaning intervals and the cleaning method [3].
The indications on the derivation of MF are available in CIE 97-2005, where according to the type of luminaire, the inspection and cleaning interval in that specific environment and the category of interior cleaning, the maintenance factor is determined through the following formula [5]:

$$MF = LLMF \cdot LSF \cdot LMF \cdot RSMF \tag{2.3}$$

Where:

- $LLMF$ (Lamp Lumen Maintenance Factor) takes into account the decrease in luminous flux following the aging of the lamp;
- LSF (Lamp Survival Factor) takes into account the difference in the duration of the individual lamps compared to the average life: for the immediate replacement of a defective lamp, $LSF = 1$;
- LMF (Luminaire Maintenance Factor) takes into account the decrease in luminous flux following the aging of the luminaire and depends on its shape and its propensity to collect dirt;
- $RSMF$ (Room Surface Maintenance Factor) takes into account the decrease in the luminous flux following the aging of the environment surfaces.

In general, the following coefficients valid for the maintenance and decay factor can be used:

Reduction	m	d
Ordinary	0.8	1.25
High	0.7	1.43
Very high	0.6	1.67

Table 2.4: Typical maintenance and decay factors, with d = 1/m.

For a long list of activities, the standard indicates the recommended values of illumination on the task surface, maximum UGR and minimum R_a, plus some additional notes for specific situations. About educational buildings, EN 12464 [3] defines:

Type of area, task or activity	$E_{m,min}$ [lux]	$UGR_{L,max}$ –	$U_{0,min}$ –	$R_{a,min}$ –
Classrooms, tutorial rooms	300	19	0.60	80
Classroom for evening classes and adults education	500	19	0.60	80
Auditorium, lecture halls	500	19	0.60	80
Black, green and white boards	500	19	0.70	80

Table 2.5: Lighting requirements for interior areas, tasks and activities.

The Average Illumination (E_m) refers to the surfaces related to the visual task which vary in height depending on the use case;

The Uniformity (U_0), defined as E_{min}/E_m, in the task area shall be not less than the minimum uniformity values given in Tab.2.5;

The Unified Glare Rating (UGR_L) is variable depending on the point and direction of observation, it is therefore appropriate to calculate multiple values so as to be able to affirm with high probability that the limit value, which corresponds to the perception of harassing glare, can never be exceeded.

The color rendering index (R_a) depends on the type of lamp installed and offers the measure of the degree of compliance of the observer's perception for the colors of the objects illuminated by the source placed in the room.

2.4.2 Daylight in school spaces

Another reference standard for school buildings is UNI EN 10840: 2007 [4] that specifies the general criteria for the artificial and natural lighting of classrooms and other school premises, so as to guarantee the general conditions for the well-being and safety of students and other school users. The standard is divided into two parts: the first is dedicated to artificial lighting and the second to natural lighting. The section of interest is the second, since the regulation is essentially limited to repeating what has already been reported on the more generic EN 12464-1 on artificial lighting.

The new concepts introduced in daylight are (considering light from the entire celestial vault, without direct sunlight):

- Average daylight factor, η_m: ratio expressed in % between the average illuminance of the environment, E_m, and the illuminance E_0 on an external horizontal surface, in the same conditions of time and space;

$$\eta_m = \frac{E_m}{E_0} \qquad (\%) \tag{2.4}$$

  Where:

  - E_m is the average illuminance value detected inside, in lux;
  - E_0 is the external average illuminance value, in lux.

- Max point of daylight factor, η_{max}: ratio between the maximum illuminance at a point inside the room E_{max} and the illuminance E_0 on an external horizontal surface, in the same conditions of time and space;

- Min point factor of daylight, η_{min}: ratio between the minimum illuminance in a point inside the room E_{min} and the illuminance E_0 on an external horizontal surface, in the same conditions of time and space.

In order to ensure adequate distribution of natural lighting, the following values of the average daylight factor must be guaranteed:

Type of environment, visual task or activity	η_m (%)
Classrooms	≥3
Blackboard	–
Auditorium, lecture halls	≥2

Table 2.6: Average daylight factor requirements for interior areas, task and activities, without any contribution due to artificial light.

For the average value, the entire surface of the room is taken into consideration (h = 0.80 m) and the following formula can be used referring to a simplified model of the environment (implemented in Dialux):

$$\eta_m = \frac{A_f \cdot t}{A_{tot} \cdot (1 - r_m)} \cdot \frac{E_{0v}}{E_0} \cdot \psi \tag{2.5}$$

Considering:

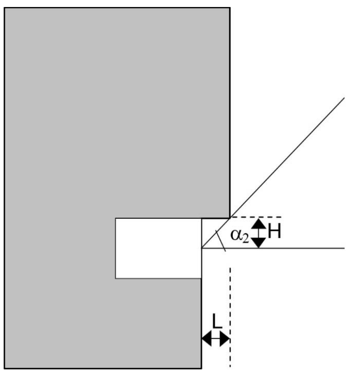
$$\varepsilon = \frac{E_{0v}}{E_0} \tag{2.6}$$

we obtain:

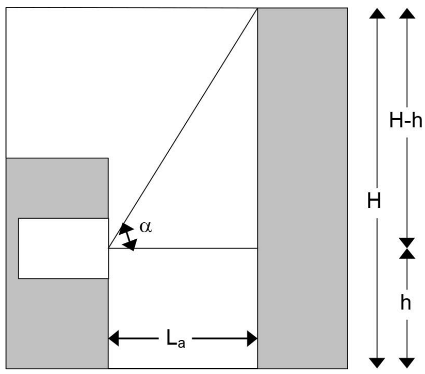
$$\eta_m = \frac{A_f \cdot t \cdot \varepsilon}{A_{tot} \cdot (1 - r_m)} \cdot \psi \tag{2.7}$$

Where:

- E_0 is the external average illuminance value produced by the celestial vault, in lux;
- E_{0v} is the external lighting on the vertical glass surface, in lux;
- A_f is the area of the window surface, excluding the frame, in m^2;
- t is the light transmission factor of glass;
- ε is the window factor, representative of the celestial vault position seen from the center of gravity of the window (Fig.2.5);
- A_{tot} is the total area that delimit the environment, in m^2;
- r_m is the average light reflection factor of the surfaces that delimit the environment;
- ψ is the reduction factor of the window factor (Fig.2.6).



(a) Facade obstruction.



(b) External obstruction.

Figure 2.5: The calculation of the window factor changes according to the type of obstruction: for facade obstruction $\varepsilon = \frac{\sin \alpha_2}{2}$; for external obstruction $\varepsilon = \frac{1 - \sin \alpha}{2}$. If there are both facade and external obstruction $\varepsilon = \frac{\sin \alpha_2 - \sin \alpha}{2}$.

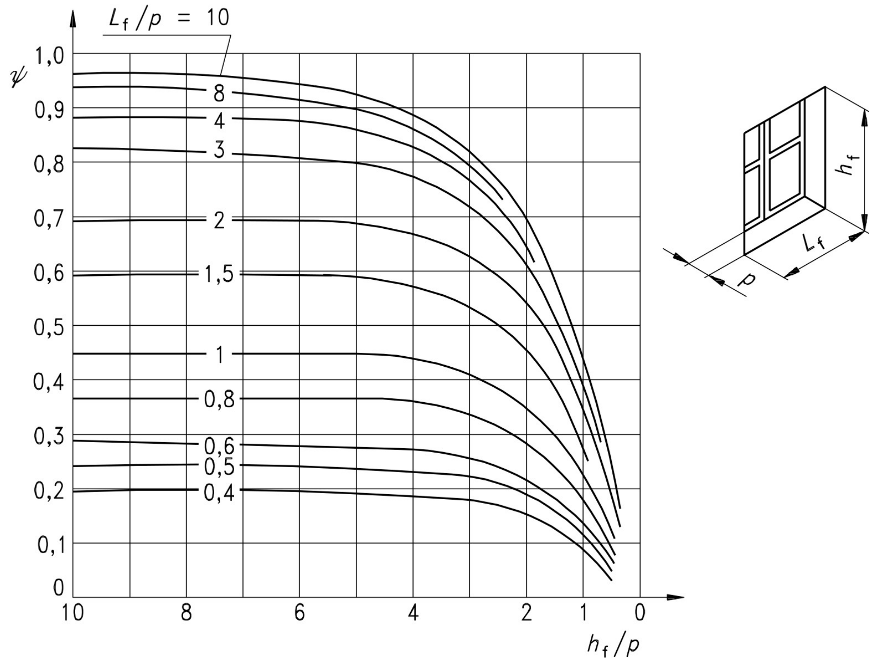


Figure 2.6: Determination of the reduction factor: L_f is the window width; h_f is the window height and p is the distance between window and the outer edge of the wall.

In addition to the glare due to luminaires, it's necessary to consider the glare caused by natural light that filters through the glass surfaces. This type of glare occurs especially in situations in which the glass surfaces are very large compared to the floor. The UGR fee for natural light is the DGI, defined as:

$$DGI = 10 \log \sum_{i=1}^{n} G_i \tag{2.8}$$

where G_i indicates the glare constant calculated for each portion of the source, primary and secondary, seen through the window (sky, obstructions, ground).

Some parameters that define G_i are difficult to calculate and the formula is therefore not easy to use. Recent experimental studies show that glare due to a single window essentially depends on the luminance of the source, highlighting how glare can be considered practically constant for all indoor environments with windows larger than 2% of the floor surface and therefore exclusively variable according to the luminance of the source and the average reflection factor of the internal environment. In this case, therefore, the control of natural glare essentially depends on the luminance conditions of the portion of the sky framed by the glass surface. To be precise, however, also the size and position of the glass surface, the luminance contrast between the internal surfaces of the environment determined by the relative light reflection factors, the possible presence of internal or external screens, etc., influence the onset of glare phenomena. Particularly important is the reflection factor of the ceiling and of the surfaces immediately adjacent to the glass surface. For classrooms the limit value of the DGI is 21.

2.5 Light and energy

In addition to satisfying visual comfort in indoor environments, great attention is given to the assessment of energy needs. The reduction of energy consumption in public buildings is a priority indicated in the European Directive 2002/91/EC, recast in the Directive 2010/31/EU (Energy Performance of Buildings Directive [7]), which promotes the improvement of the energy performance of buildings. The first was implemented in Italy by D.Lgs. 192/2005 and by the subsequent D.L. 63/2013, following which the Ministry of Economic Development in 2015, with D.M. 26/06 [8], adapted the "National guidelines for the energy certification of buildings", established the application of the methodologies for calculating energy performance, with minimum buildings requirements, and defined the reference schemes and methods for the compilation of the technical project report.
The obligations relating to lighting are the determination of the energy performance index, for the purpose of the building's energy performance certificate, and the installation of an automatic lighting control system to reduce consumption.
According to D.M. 26/06/15 the determination of the energy performance index for lighting is necessary for buildings belonging to categories E.1 – E.7 (Tab. 2.7). However, this index must be calculated only for new buildings or for major first-level renovations, following EN 15193 [9]. For existing buildings subject to major second-level renovations, or under energy requalification, in case of replacement of individual luminaires, it is sufficient to use new luminaires that comply with the minimum requirements defined by the community regulations issued pursuant to directive 2009/125/EC (Eco–Design directive) and 2010/30/EU (Energy labeling).
Through the D.M. 11/10/2017 of the Ministry of the Environment [10] the minimum environmental criteria (CAM) are established for the entrusting of design services and works for new construction, renovation and maintenance of public buildings; they are applied in public bidding processes and they are aimed at public works contracting stations to enforce their respect.

Category	Description
E.1	Residential and similar buildings
E.2	Office buildings and similar
E.3	Buildings used as hospitals and similar
E.4	Buildings used for recreational activities and similar
E.5	Buildings used for commercial and similar activities
E.6	Sports buildings
E.7	Buildings used for school activities at all levels and similar

Table 2.7: List of building categories (D.P.R. 412/1993) for which the assessment of the energy performance index for lighting is required.

The European Directive 2010/31/EU recommends an assessment of the energy needs of buildings to define the level of environmental comfort. Among the factors that most determine energy consumption (use for heating, cooling, ventilation, hot water), artificial lighting is one of the major sources of consumption in non-residential buildings, constituting 20 – 30% of the building total energy load [34].
In environments such as schools or public structures in general, where users are passive, it is possible to have a more controlled consumption. Unlike active users, in which occupants use the light only when necessary through manual switching on and off (such as in residences), in offices and schools the light remains on throughout the working day, even in unused spaces.
Lighting control can significantly reduce energy demand: the interventions concern an appropriate use of the luminaires and the maximization of the use of natural light, using not only low environmental impact luminaires but also integrating instruments that regulate their use. The correct integration of natural and artificial light is an effective method for reducing energy needs and obtaining maximum visual performance.

The standard EN 15193 specifies the methodology for evaluating the energy performance of lighting systems in residential and non-residential buildings. The procedure described in the standard assumes that the installations comply with the practices dictated by EN 12464-1 and it can be applied to new buildings, already existing or renovated. The methodology used involves the use of an indicator, the LENI, to measure the energy efficiency of light installations.
Published in 2017, this standard represents the update of the previous one of 2007, which presented a less detailed approach to estimate the contribution of natural lighting in energy performance. Before its publication, in fact,

numerous researches were carried out which demonstrated its limitations. A research conducted by ENEA developed an approach that took into account the outdoor environment by determining the Daylight Factor, calculated in different positions with respect to the window, and applied in three cities with different climatic data. The results resulted in greater precision than the simplified LENI method, which overestimated the results by $40 - 50\%$ [35]. In another research, Zinzi and Iatauro showed how the 2007 standard is based on an underestimation of the contribution of natural light and an overestimation of energy consumption [36].
The new legislation therefore considers the effects of important factors such as latitude, climate, orientation and the presence of shielding, providing more detailed and reliable results.

The LENI (Lighting Energy Numeric Indicator) expresses the energy consumed in the building per unit area in a year. The calculation of the LENI is based on the integration of the power absorbed over time, according to the formula:

$$LENI = \frac{W_{L,t} + W_{P,t}}{A} \qquad \left(\frac{kWh}{m^2 year}\right) \tag{2.9}$$

where:

- $W_{L,t}$ is the energy requirement necessary for luminaires to guarantee the lighting conditions in terms of average illuminance maintained;
- $W_{P,t}$ expresses the energy requirement for the operation of the emergency lighting devices and the standby of the various lighting control systems that may be present.

Since 2007, three different methods can be used to estimate values. The new legislation exposes the same three methods, but considering multiple factors in the final evaluation.
The first method (Comprehensive method) takes into account numerous factors assessed with each application. This method covers the calculation of the energy requirements of lighting systems in residential and non-residential buildings where a comprehensive lighting system design has been performed. This calculation method is suitable for use during the design of new or refurbished buildings and for assessing existing buildings.
The second one (Quick calculation method) covers the calculation of the energy requirements of lighting systems for residential and non-residential buildings where a comprehensive lighting system design has not been performed. The method makes use of quick calculation and default data and the result gives budget energy values.
The third one (Direct metering method) covers the direct measurement of

the energy used by lighting system in residential and non-residential buildings by segregated direct metering and it gives the true value of energy used by the lighting system and can be used to verify the values obtained by the calculated methods.
The calculation procedure related to method n.2 will be illustrated below as it was considered the most suitable for the topic of this thesis [9].

Considering the values of t_D and t_N shown in the table B.2 of Annex B as default values ($t_D = 1800$ h and $t_N = 200$ h), the budget installed power required for new electric lighting systems shall be estimated using a standard set of assumptions and procedures. The budget installed power required for an area in the building is estimated considering the power density of the area, the mantained illuminance and correction factors depending on MF, E_{task} and E_{surr} and the lamp type (Annex C).
Default data for the required standby energy for battery charging of emergency luminaires (W_{pe}) and for standby energy for automatic lighting controls (W_{pc}) are provided in table B.1 of annex B:

$$W_{pe} = 1.00 \qquad \left(\frac{kWh}{m^2 year}\right) \tag{2.10}$$

$$W_{pc} = 1.50 \qquad \left(\frac{kWh}{m^2 year}\right) \tag{2.11}$$

Default values for the Occupancy dependency factor (F_O) can be obtained in table B.7 of Annex B as function of F_A and the lighting control system, where F_A is given in Annex E, according to the use of the building: considering room by room calculation $F_A = 0.40$ for lecture halls.
The quick method for estimating F_D for vertical facades shall be calculated by selecting the zone segmentation as described in Annex F and use of the following equations:

$$D = 0.34 \cdot (4.13 + 20 \cdot I_{Tr,j} - 1,36 \cdot I_{RD,j}) \tag{2.12}$$

where:

$$I_{Tr,j} = \frac{A_{Ca}}{A_D} \tag{2.13}$$

and

$$I_{RD,j} = \frac{a_D}{h_{Li} - h_{Ta}} \tag{2.14}$$

This two formulae are given in Annex F and they are respectively the Transparency index and the Space depth index; they depend on the characteristics of windows and depth of daylight area.

For south facing facades without shading or glare protection, or for east, west and north facing facades:

$$F_{D,S} = 0.65 \cdot F_{D,S,SNA} + 0.25 \tag{2.15}$$

where $F_{D,S,SNA}$ is given in table B.3 of Annex B for various values of Daylight Factors (D).
Then Daylight supply dependency factor (F_D) is calculated:

$$F_D = 1 - 0.52 \cdot F_{D,S} \tag{2.16}$$

Constant illuminance dependency factor (F_C) is provided in table B.8 of Annex B depending on the lighting system.
In the end the energy calculation can be obtained:

$$LENI_{sub} = \left\{ F_C \cdot \left(\frac{P_j}{1000} \right) \cdot F_O \cdot [(t_D \cdot F_D) + t_N] \right\} + 1.0 + 1.5 \tag{2.17}$$

where:

- $LENI_{sub}$ is referred to the area, in kWh/m^{2}year;
- F_C is constant illuminance factor for the area;
- P_j is the power density of the area, in W/m^2;
- F_O is the occupancy dependency factor for the area;
- t_D is daylight time for the area, in hours;
- F_D is the daylight dependency factor for the area;
- t_N is the daylight absence time for the area, in hours;
- t_y are the annual operating hours for the area, in hours.

The LENI value for the entire building is calculated by the followind equation:

$$LENI = \frac{\sum_{i=1}^{n} (LENI_{sub,i} \cdot A_i)}{A} \qquad \left(\frac{kWh}{m^2 year} \right) \tag{2.18}$$

considering A_i as the total useful areas, in m^2, and A as the total useful floor area of the building, in m^2 [9].

Chapter 3

Lecture halls current status

3.1 Case study description

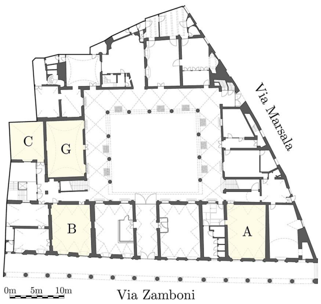
Palazzo Malvezzi-Campeggi si located in Via Zamboni, 22, in Bologna, in front of the Basilica of San Giacomo Maggiore and in the north-east area of the city centre. It was built around the mid-16th century by Andrea and Giacomo Marchesi from Formigine on an old structure that previously belonged to Giovanni II Bentivoglio.
The large room on the main floor is the work of the architect Giuseppe Ambrosi, who also organized the arrangement of the paintings made in 1735 by the landscape painter Carlo Lodi and the figure painter Antonio Rossi, in which the war prowess of the major exponents of the Malvezzi family are represented on the walls, hence the name “Salone delle Armi”. The stuccos of Carlo Nessi hold the coats of arms of the Malvezzi and Campeggi families. Two large bronze wings and three magnificent tapestries also came from Palazzo Campeggi (today Bevilacqua in Via d’Azeglio), while the decorations in the other rooms were entrusted to Vittorio Bigari, Gioacchino Pizzoli and Giovanni Benedetto Paolazzi.
During second world war the palace was seriously damaged and left in neglect for a long time; subsequently it was restored between the 70s and 80s under the direction of the Superintendency of Artistic and Historical Heritage of Bologna and currently the building is home to the Law Faculty of the University of Bologna, now under renovation again.

The university classrooms in question are cases A, B, C, G on the ground floor, case D on the first floor, case E on the second floor and three lecture room: Salone delle Feste and Salone delle Armi on the first floor and Aula Magna on the second floor. The classrooms have very different spatial characteristics, briefly described in table 3.1.

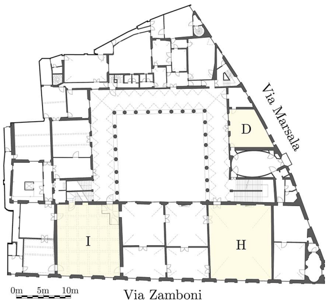
Case	Name	L (m)	W (m)	H (m)	Ceiling
A	0.2	9,8	7.3	5.3	vault with lunettes
B	0.4	9.0	7.0	5.3	vault with lunettes
C	0.5	6.6	6.1	4.7	cloister vault
D	1.9	7.0	5.2/8.6	3.8	flat
E	2.1	6.7	6.2	4.6	exposed beams
F	Aula Magna	15.0	6.7/14	4.0/2.0	stepped and sloped
G	0.6	10.4	6.9	5.6	cloister vault
H	Sala Armi	14.0	12.0	9.3/3.3	cloister vault
I	Sala Feste	13.5	11.4	8.0	coffered

Table 3.1: Dimensional data of lecture halls inside Palazzo Malvezzi-Campeggi.

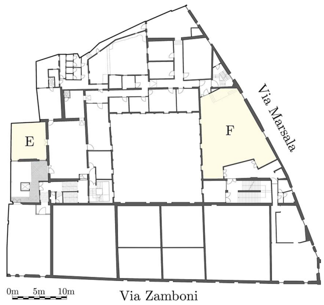
Figure 3.1: Palazzo Malvezzi-Campeggi, in Via Zamboni, in front of the Basilica of San Giacomo Maggiore, next to Piazza Verdi.



(a) Ground floor.

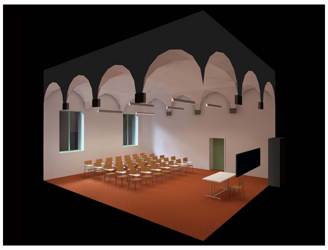


(b) First floor.

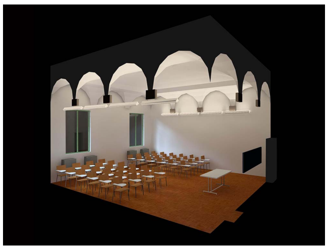


(c) Second floor.

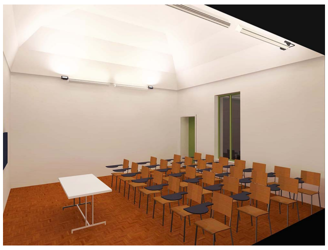
Figure 3.2: Cases position inside Palazzo Malvezzi-Campeggi.



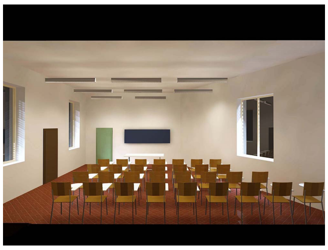
(a) Case A.



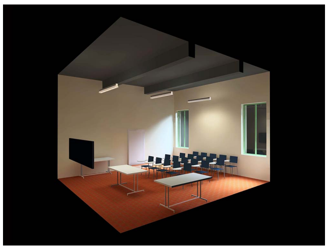
(b) Case B.



(c) Case C.



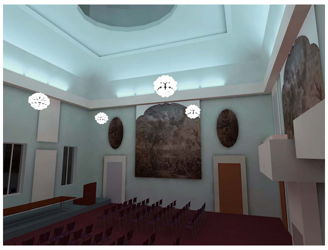
(d) Case D.



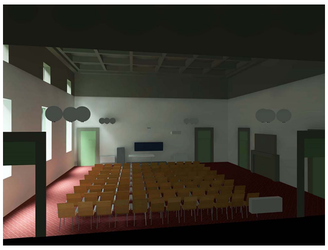
(e) Case E.

(f) Case F.

(g) Case G.



(h) Case H.



(i) Case I.

Figure 3.3: Case studies of Palazzo Malvezzi-Campeggi.

3.2 Procedures

In order to create the models on Dialux, a geometric survey of the case studies was conducted, with the obtaining of photos of the current state of the premises, looking for the type of luminaires and the materials and colors of the main surfaces and objects of interest.
The strategy identified for the classrooms simulations is divided into:

- geometric relief of the classrooms in plan and elevation;
- realization of plans and elevations on AutoCAD;
- cleaning of the .dwg files from the elements of excessive detail not necessary for the lighting simulations;
- import of classroom plans into Dialux;
- realization of walls, characterized by opaque or glazed surfaces, false ceilings and type of ceiling (vaults, dome, etc.).

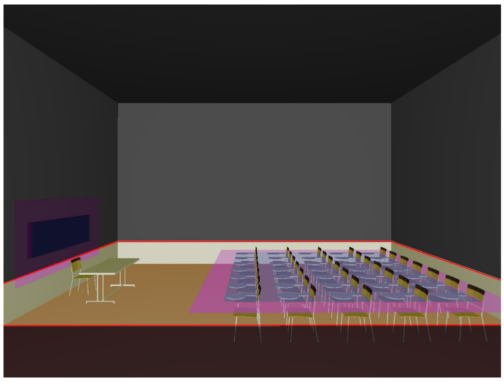
The furnishing of the spaces has not been defined in the smallest details as neglecting small elements does not significantly alter the results of the simulations, especially if these are placed in the marginal areas of the rooms. In defining all the elements, it is important to underline that Dialux considers surfaces to be perfectly diffusing and therefore the material and its roughness do not influence the reflections arising from the interaction with light.
The parameters that influence the lighting calculation are the reflection coefficient and the surface color; by changing the reflection coefficient the hue of the selected color changes. An increase in the coefficient corresponds to a reduction of the hue of the chosen color while a decrease corresponds to a shift towards a darker tone. The colors were chosen for similitude by inspecting the premises; the reflection coefficients were assumed by exploiting the data present in the article by V. Costanzo et al. about natural lighting in a historic building used for school use [37] and using the values recommended by the software.
Subsequently each classroom was positioned in a geographically correct way in view of the simulation with daylight.

For all simulations the same configuration of calculation surfaces was used (fig. 3.4); the strategy with which they were positioned tried to get as close as possible to the needs of the analyzed environments.
For each room, the software automatically creates a surface (in Dialux: *Useful Surface*) at 0,80 m in height from the floor, this will be used to evaluate the average illuminance of the environment.

Figure 3.4: Calculation surfaces in a typical classroom.

In the classrooms two work areas have been inserted (in Dialux: *Visual task area*): one at a height of 0,70 m from the floor for the global area of the desks and another one for the blackboard; the surrounding areas were set in a 0,50 m band to verify that the band adjacent to the task area ensures an adequate level of uniformity; considering the surface of the room, a single background area was then identified for both workstations and at their same height.

(a) Visual task areas of desks and blackboard.



(b) Useful Surface at 0,80 m in height from the floor.

Figure 3.5: Calculation surfaces adopted for every classroom.

Each classroom was verified following the prescriptions of the standards, reported below in Tab. 3.2, 3.3, considering not only what is provided by EN 12464 [3] and UNI 10840 [4], relating to schools, but also some references from previous regulations, UNI 10380 [6], whose main definitions are still in use in the practical and working environment:

Type of area, task or activity	$E_{m,task}$ [lux] (min)	$E_{m,surr}$ [lux] (min)	$E_{m,back}$ [lux] (min)
Classrooms, tutorial rooms	300	200	67
Auditorium, lecture halls	500	300	100
Blackboards	500	300	100

Table 3.2: Illuminance requirements for task, surrounding and background areas. In accordance with Tab. 2.2, as established by EN 12464-1, the illuminance in the area adjacent to the visual task must be less since the large spatial variations of illuminance in the activity area can induce visual stress and discomfort.

Type of area, task or activity	$U_{0,task}$ – (min)	$U_{0,surr}$ – (min)	$U_{0,back}$ – (min)
Classrooms, tutorial rooms	0.60	0.40	0.10
Auditorium, lecture halls	0.60	0.40	0.10
Blackboards	0.70	0.40	0.10

Table 3.3: Uniformity requirements for task, surrounding and background areas. In accordance with the previous table (Tab. 3.2) it is necessary to ensure uniformity of light distribution within the visual task area but also in the surrounding space, in this way the work environment will be well balanced and comfortable.

With regard to the current state, the task area relative to classrooms and tutorial rooms is considered in this paper because it has the minimum requirements for good general lighting comfort in school premises.

3.3 Simulation results

This section illustrates the current condition of the classrooms obtained through simulation on Dialux for comparison with photos in situ, reporting the same lighting conditions (artificial and/or natural), setting a maintenance factor of 0.60, taking into account the following parameters, compliant with the standard CIE 97-2005 [5] (Tab. 3.4):

Inspection interval for schools	3 years
Times/years	0,33
Environment	Clean (C)
Luminaire type	F
Schools burning hours	1900 hours/year
Cleaning and re-lamp	every 5700 hours
Burning hours in thousand hours	5,7
LLMF	0,89
LSF	1,00
LMF	0,79
RSMF	0,94
MF	0,63

Table 3.4: Maintenance factor considered for the current state of the classrooms.

To obtain a simulation that was as similar as possible to the current state of art, the neighborhood adjacent to Palazzo Malvezzi-Campeggi was rebuilt directly on Dialux, in order to guarantee a projection of sunlight into the classrooms as close as possible to reality (fig. 3.6).

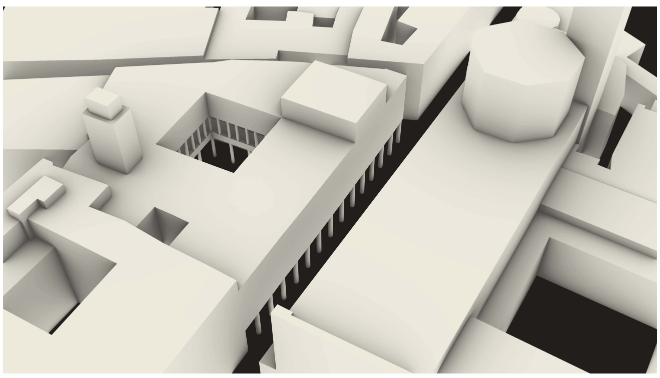


Figure 3.6: Modelling reconstruction around Palazzo Malvezzi-Campeggi.

Case A

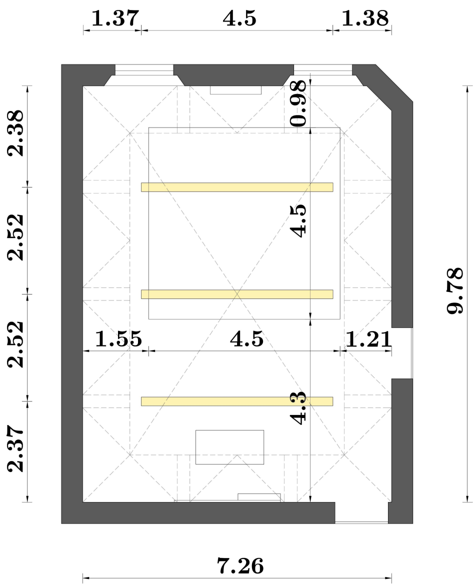


Figure 3.7: Case A plan; height of the luminaires at 3.80 m.

The classroom is located on the ground floor and faces the external portico, Via Zamboni side, through two high windows; it is rectangular in shape, medium-small in size and capacity (approximately 300 – 350 m^3 with 40 – 50 seats), with rigid plastered walls and a vaulted ceiling with lunettes. The flooring is in cotto tile and the seats are in wood with reclining benches. Lighting is provided exclusively by suspended rectangular linear sources placed parallel to the rows of seats and they generate direct light over the entire classroom surface.

The model used in the simulation was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting, considering 6 rectangular suspended lamps, fluorescent tube type, at 3.80 m of height (fig. 3.9); colors and materials choosed for the simulation are represented in Tab. 3.5.

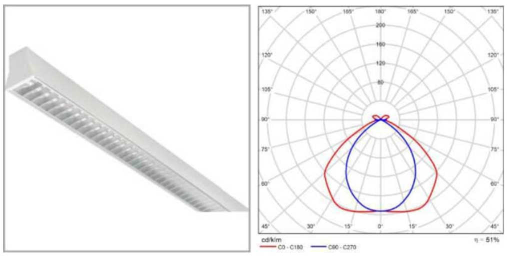
(a) Real photo of case A.

(b) Dialux rendering of case A.

Figure 3.8: Comparison between real photo and Dialux rendering, obtained reporting the same light conditions with both natural and artificial light, considering 6 rectangular suspended fluorescent lamps at 3.80 m of height.

Object	Colour/material	r
Walls	yellowish white	0.77
Ceiling	yellowish white	0.77
Floor	cotto tile	0.15
Windows	soft green	0.32
Doors	brown	0.08
Seats	wood	0.26
Desks	white	0.86

Table 3.5: Case A: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.9: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case A: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

Despite the contribution of natural lighting, the minimum average illuminance value required by EN 12464-1 [3], equal to 300 lx, is not reached; furthermore, if the lighting system is exclusively directed towards the visual task, there is glare at the level of the desks (UGR = 20.2).
This type of distribution doesn't work both from a technical and an architectural point of view: on one hand the anti-glare plates of the luminaires should be placed perpendicular to the visual ray in order to delete glare and prevent direct vision of the lamp; on the other hand, the exclusively direct distribution of the luminous flux creates a non-uniformity of shadows on the walls, also clashing with the architectural typology of the ceiling, vaulted with lunettes (fig. 3.10).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	271	0.64	20.2	🟥
	235	0.62	–	🟩
	142	0.42	–	🟩
Blackboard	99.4	0.94	20.2	🟥
	89.2	0.91	–	🟥
	141	0.42	–	🟩
Useful surface	207	0.25	–	🟥

Table 3.6: Case A: Dialux previsional evaluation for visual comfort.

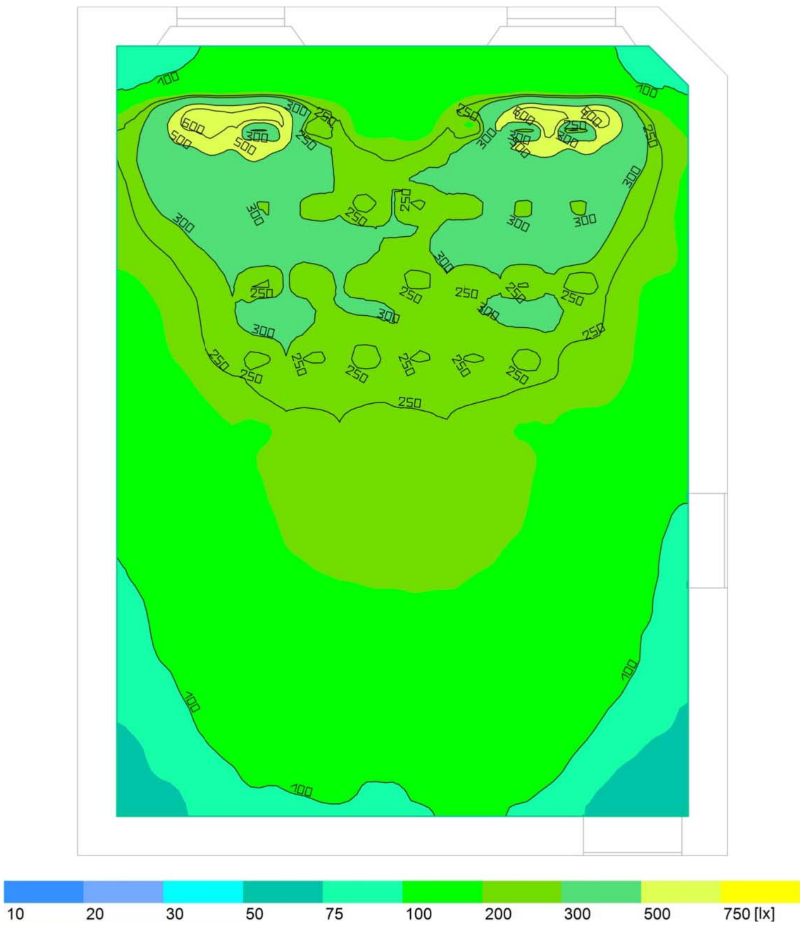


Figure 3.10: Isolux map of useful surface in Case A: $E_m = 210$ lx with $U_0 = 0.25$ at 0.80 m of height from the floor.

Being on the ground floor overlooking the portico of Via Zamboni, with an average height of 6 m, and located in front of the Basilica of San Giacomo Maggiore, which is on average 21 m high, the room in question receives a very low amount of natural light. Very low illuminance values are reached, which do not even reach 50 lux.

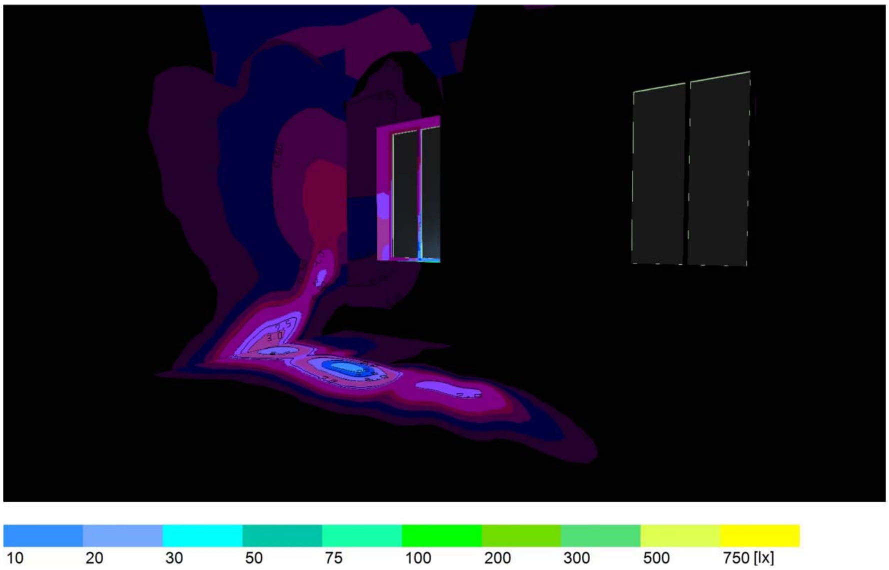


Figure 3.11: Daylight simulation results by Dialux in Case A.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.01	■

Table 3.7: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.12) was calculated

considering the frontal and facade obstruction ($\varepsilon = 0.10$). In this classroom the two windows are the same and have the same characteristics.

Measure	Symbol	Value
Average reflection factor	r_m	0.56
Window area	A_f [m^2]	2.82
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	318
Window factor	ε	0.10

Table 3.8: Case A parameters considered in daylight factor calculation.

$$\eta_m = \frac{2 \cdot 2.82 \cdot 0.90 \cdot 0.10}{318 \cdot (1 - 0.56)} \cdot 0.90 = 0.01 \tag{3.1}$$

The result is lower than that reported by the software but it does not differ much from the latter therefore it is confirmed that the quantity of natural light in the room is insufficient.

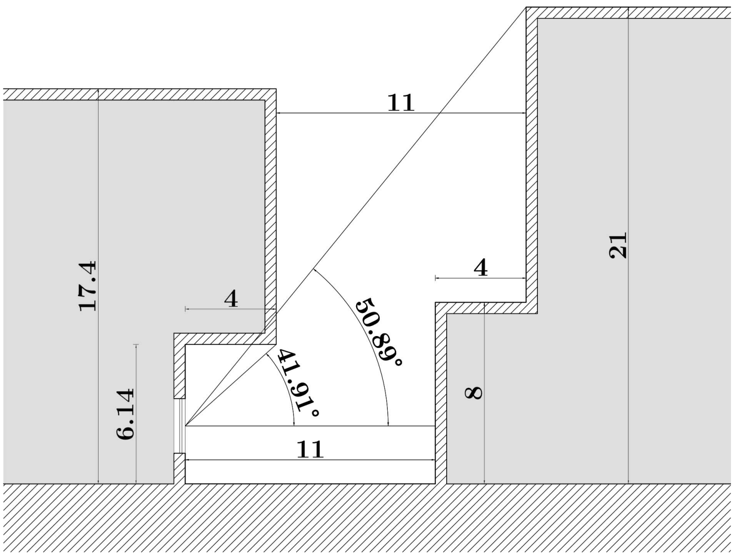


Figure 3.12: Angles considered for window factor in Case A.

Case B

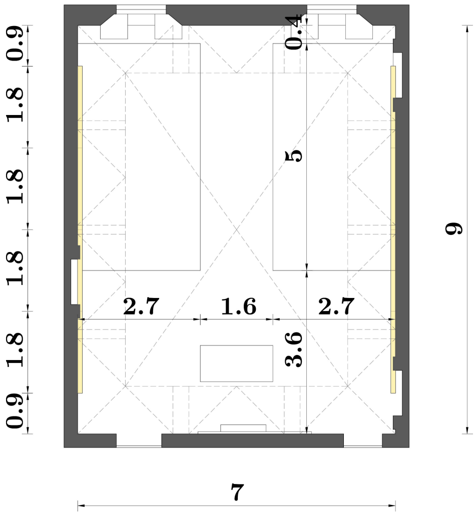


Figure 3.13: Case B plan; height of the luminaires at 3.80 m.

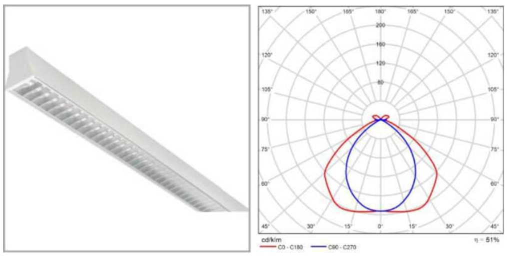
As Case A, this classroom is located on the ground floor and faces the external portico, Via Zamboni side, through two high windows; it is rectangular in shape, medium-small in size and capacity (approximately 300 – 350 m^3 with 40 – 50 seats), with rigid plastered walls and a vaulted ceiling with lunettes. The flooring is in wood and the seats in wood with reclining benches. Lighting is provided by linear wall sources placed at an angle to the vertical plane in order to generate indirect light on the ceiling.
The model used in the simulation was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting, considering 8 rectangular linear wall mounted lamps, fluorescent tube type, positioned at 3.80 m of height (fig. 3.15) with an angle of 45° to the vertical plane; colors and materials choosed for the simulation are represented in Tab. 3.9.

(a) Real photo of Case B. (b) Dialux rendering of Case B.

Figure 3.14: Comparison between real photo and Dialux rendering, obtained reporting the same light conditions with both natural and artificial light, considering 8 rectangular wall mounted fluorescent lamps at 3.80 m of height.

Object	Colour/material	r
Walls	yellowish white	0.77
Ceiling	yellowish white	0.77
Floor	wood	0.15
Windows	soft green	0.32
Doors	soft green	0.32
Seats	wood	0.26
Desks	white	0.86

Table 3.9: Case B: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.15: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case B: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

The disposition of the luminaires is correct because the inclination, with respect to the vertical plane, prevents direct vision of the lamp tubes, thus preventing the presence of glare. This is also positive for the flow distribution and uniformity on the walls: indirect lighting in this case exploits the shape of the classroom (vaulted with lunettes) and the luminous component that reaches the student's eye is exclusively reflected, especially from the ceiling. However, the illuminance values don't meet the standard requirements [3] and the contribution of daylight is not enough (fig. 3.16).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	219	0.60	11.2	🟥
	141	0.15	–	🟥
	117	0.37	–	🟩
Blackboard	224	0.56	12.0	🟥
	142	0.13	–	🟥
	116	0.36	–	🟩
Useful surface	187	0.01	–	🟥

Table 3.10: Case B: Dialux previsional evaluation for visual comfort.

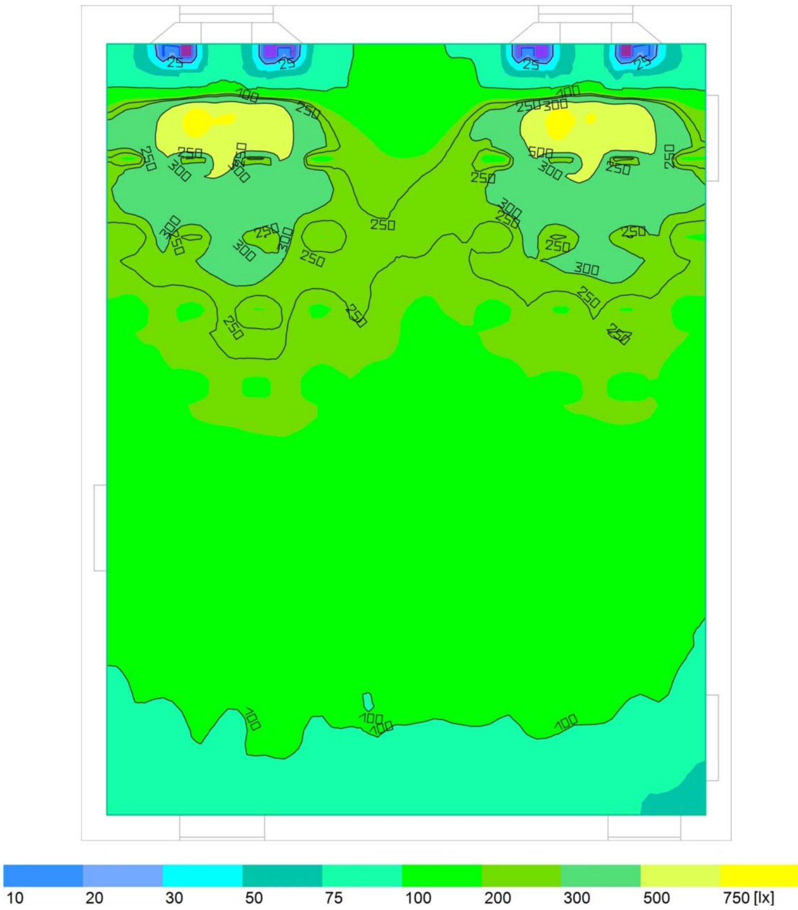


Figure 3.16: Isolux map of useful surface in Case B: $E_m = 190$ lx with $U_0 = 0.01$ at 0.80 m of height from the floor.

As Case A, this one is on the ground floor overlooking the portico of Via Zamboni, with an average height of 6 m, and located in front of the Basilica of San Giacomo Maggiore, which is on average 21 m high. This room receives a low amount of natural light, hoiher with respect to Case A because of the presence of a free space, Piazza Rossini, in front of the church.

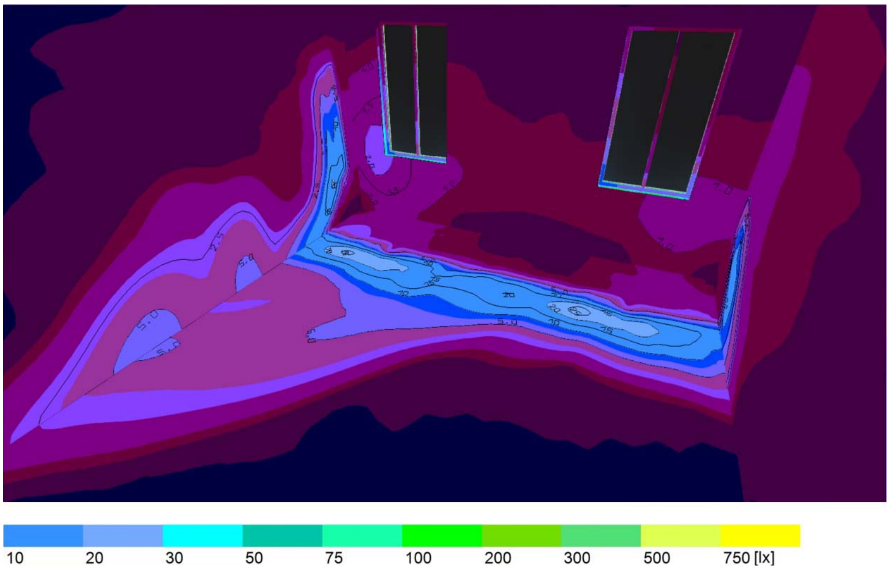


Figure 3.17: Daylight simulation results by Dialux in Case B.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.04	■

Table 3.11: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the

size of the window. Finally, the window factor (Fig. 3.18) was calculated considering the frontal and facade obstruction ($\varepsilon = 0.10$).

Measure	Symbol	Value
Average reflection factor	r_m	0.62
Window area	A_f [m^2]	2.82
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	290
Window factor	ε	0.10

Table 3.12: Case B parameters considered in daylight factor calculation.

$$\eta_m = \frac{2 \cdot 2.82 \cdot 0.90 \cdot 0.10}{290 \cdot (1 - 0.62)} \cdot 0.90 = 0.01 \tag{3.2}$$

The result is lower than that reported by the software but it does not differ much from the latter therefore it is confirmed that the quantity of natural light in the room is insufficient.

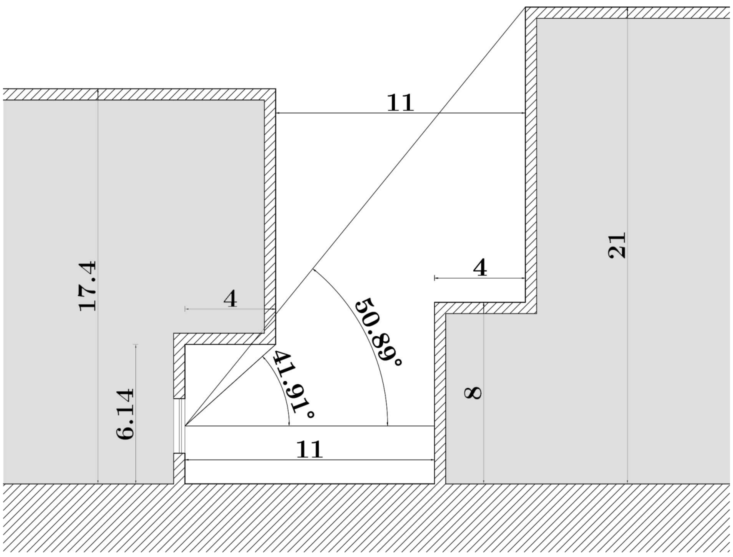


Figure 3.18: Angles considered for window factor in Case B.

Case C

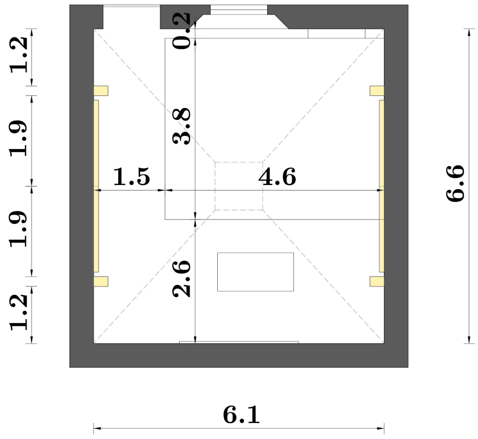


Figure 3.19: Case C plan; height of the luminaires at 3.60 m.

Small in size (200 m^3 with about 30 seats), it is located on the first floor in an internal position of the building, almost square in size and with a vaulted ceiling. Plastered walls and wooden flooring, it has a large window facing a small internal service courtyard; the seats are made of wood with reclining dark-colored benches which allows a good contrast of luminance with the student's visual task. Lighting is provided by 4 projectors and 4 linear wall sources placed at an angle to the vertical plane in order to generate indirect light on the ceiling.

The model used in the simulation was calibrated for similitude with the photos, reporting the same lighting conditions with artificial and natural lighting, considering 4 rectangular linear wall lamps, fluorescent tube type, positioned at 3.60 m of height (fig. 3.21) with an angle of 45° to the vertical plane, and 4 projectors with led lamps; colors and materials choosed for the simulation are represented in Tab. 3.13.

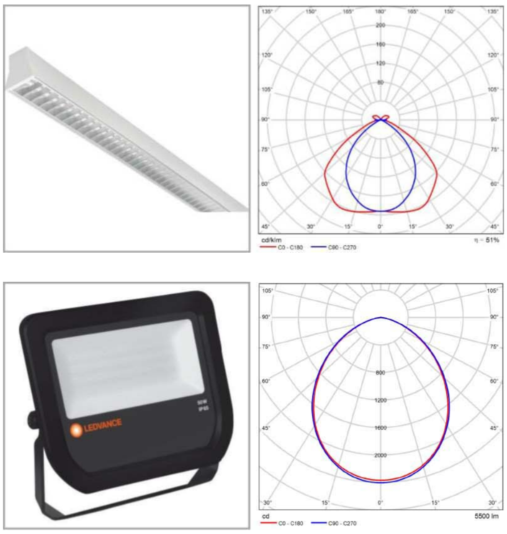
(a) Real photo of Case C.

(b) Dialux rendering of Case C.

Figure 3.20: Comparison between real photo and Dialux rendering, obtained reporting the same light conditions with both natural and artificial light, considering 4 rectangular wall mounted fluorescent lamps and 4 projectors at 3.60 m of height.

Object	Colour/material	r
Walls and ceiling	yellowish white	0.77
Floor	wood	0.15
Doors and windows	soft green	0.32
Seats	wood	0.26
Desks	black	0.05

Table 3.13: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Parameter	Value
P	50.0 W
Φ_{lamp}	5500 lm
Luminous efficiency	110.0 lm/W
CCT	4000 K

Figure 3.21: Linear lamp with two fluorescent tubes considered in Case C and led projectors, both with an angle of 45° with respect to the vertical plane.

As in Case B, the arrangement of the luminaires is correct because the inclination with respect to the vertical plane prevents direct viewing of the lamp tubes, thus preventing the presence of glare. This is also positive from the point of view of flow distribution and uniformity on the walls: indirect lighting in this case exploits the shape of the classroom (vaulted with lunettes) and the luminous component that reaches the student's eye is exclusively reflected, especially from the ceiling. Although the environment is very bright, the illuminance values do not meet the standards requirements [3] and the presence of the projectors towards the white ceiling increase glare on desks (UGR > 30).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	212	0.75	> 30	🟥
	230	0.78	–	🟩
	164	0.65	–	🟩
Blackboard	153	0.91	> 30	🟥
	152	0.75	–	🟥
	141	0.50	–	🟩
Useful surface	216	0.61	–	🟥

Table 3.14: Case C: Dialux previsional evaluation for visual comfort.

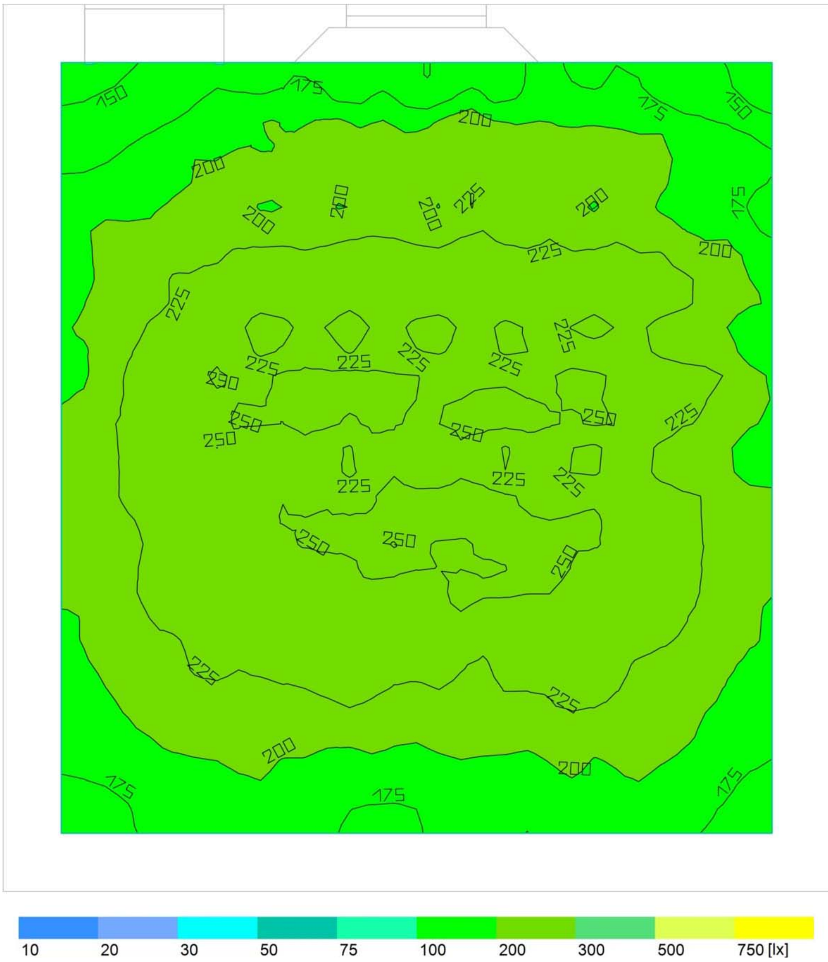


Figure 3.22: Isolux map of useful surface in Case C: E_m = 220 lx with U_0 = 0.61 at 0.80 m of height from the floor.

Being on the ground floor overlooking a small internal service courtyard 7 m wide, the classroom in question does not receive a share of daylight, in fact it does not even reach 5 lux at 12.00.

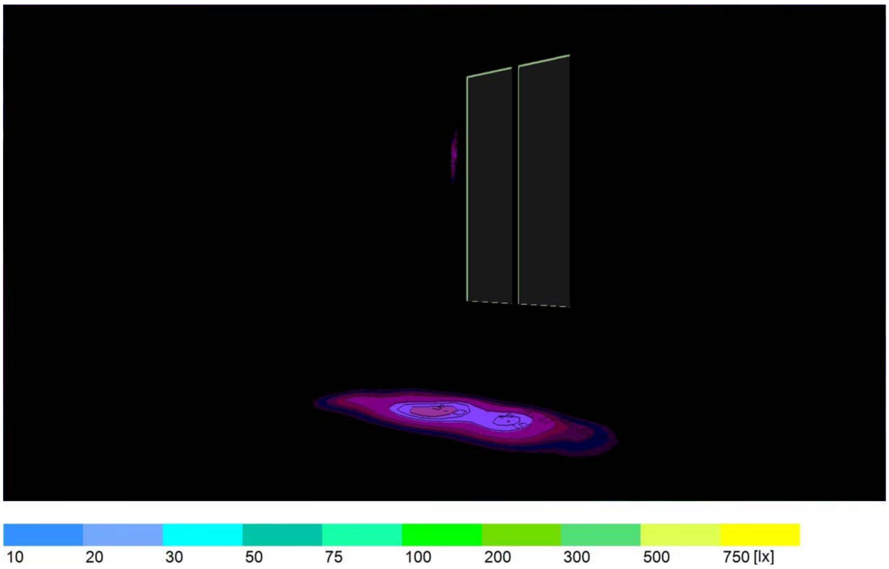


Figure 3.23: Daylight simulation results by Dialux in Case C.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.00	■

Table 3.15: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.24) was calculated considering the frontal obstruction ($\varepsilon = 0.29$).

$$\eta_m = \frac{2.52 \cdot 0.90 \cdot 0.29}{200 \cdot (1 - 0.62)} \cdot 0.90 = 0.008 \tag{3.3}$$

Measure	Symbol	Value
Average reflection factor	r_m	0.62
Window area	A_f [m^2]	2.52
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	200
Window factor	ε	0.29

Table 3.16: Case C parameters considered in daylight factor calculation.

The result is comparable with that reported by the software therefore it is confirmed that the quantity of natural light in the room is insufficient.

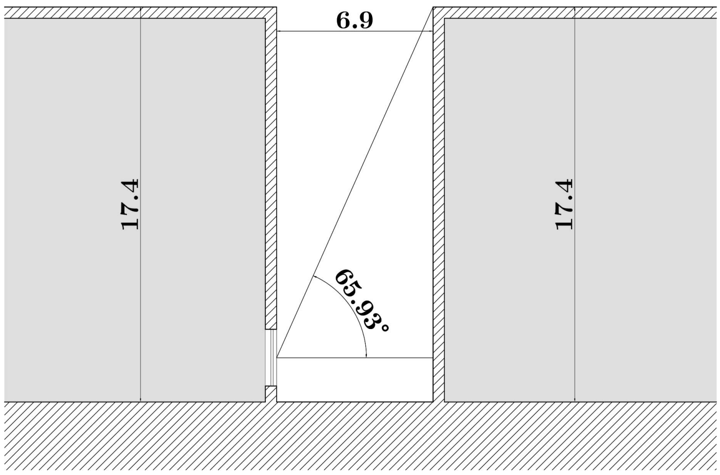


Figure 3.24: Angles considered for window factor in Case C.

Case D

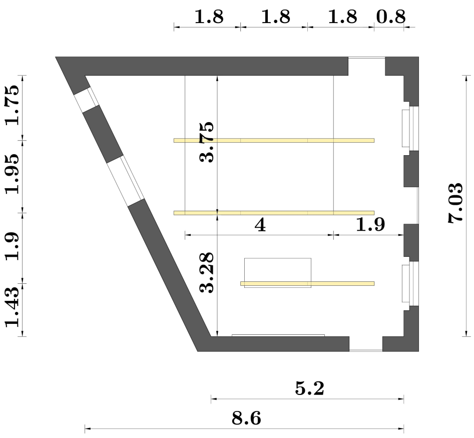


Figure 3.25: Case D plan; height of the luminaires at 3.40 m.

Placed in correspondence with Case F (which is located on the upper floor), it shares its trapezoidal shape, obviously with smaller dimensions (less than 200 m^3). It has small windows on two sides, two towards the internal courtyard of the building and two on the street side (Via Marsala); the walls are plastered and the ceiling is flat while the flooring is in cotto and wooden seats with light benches are present. Lighting is provided by suspended linear sources, placed parallel to the seating arrangement and generate direct light over the entire classroom surface.

The model used in the simulation was calibrated for similitude with the photos, reporting the same lighting conditions: in this classroom both natural and artificial lighting were considered to have 100% luminous flux emitted, considering 8 rectangular suspended lamps, fluorescent tube type, positioned at 3.40 m of height (fig. 3.27); colors and materials choosed for the simulation are represented in Tab. 3.17.

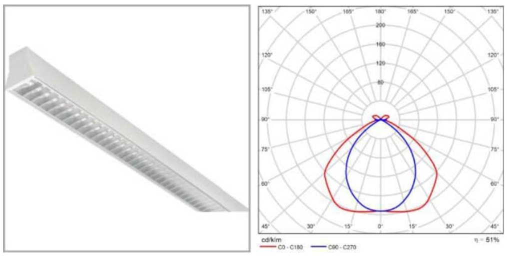
(a) Real photo of Case D.

(b) Dialux rendering of Case D.

Figure 3.26: Comparison between real photo and Dialux rendering, obtained reporting the same light conditions with both natural and artificial light, considering 8 rectangular suspended fluorescent lamps at 3.40 m of height.

Object	Colour/material	r
Walls	yellowish white	0.77
Ceiling	yellowish white	0.77
Floor	cotto tile	0.10
Windows	yellowish white	0.82
Doors	soft green	0.32
Seats	wood	0.26
Desks	white	0.86

Table 3.17: Case D: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.27: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case D: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

Despite the contribution of natural lighting, the minimum average illuminance value required by EN 12464-1 [3] is not reached; moreover the distribution is exclusively direct and this causes non-uniformity illumination of the walls.

This type of distribution doesn't work also from a technical point of view because the anti-glare plates of the luminaires should be placed perpendicular to the visual ray in order to delete glare and prevent direct vision of the lamp (fig. 3.28).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	279	0.49	15.8	🟥
	333	0.25	–	🟥
	222	0.57	–	🟩
Blackboard	181	0.83	< 10	🟥
	172	0.66	–	🟥
	206	0.33	–	🟩
Useful surface	293	0.07	–	🟥

Table 3.18: Case D: Dialux previsional evaluation for visual comfort.

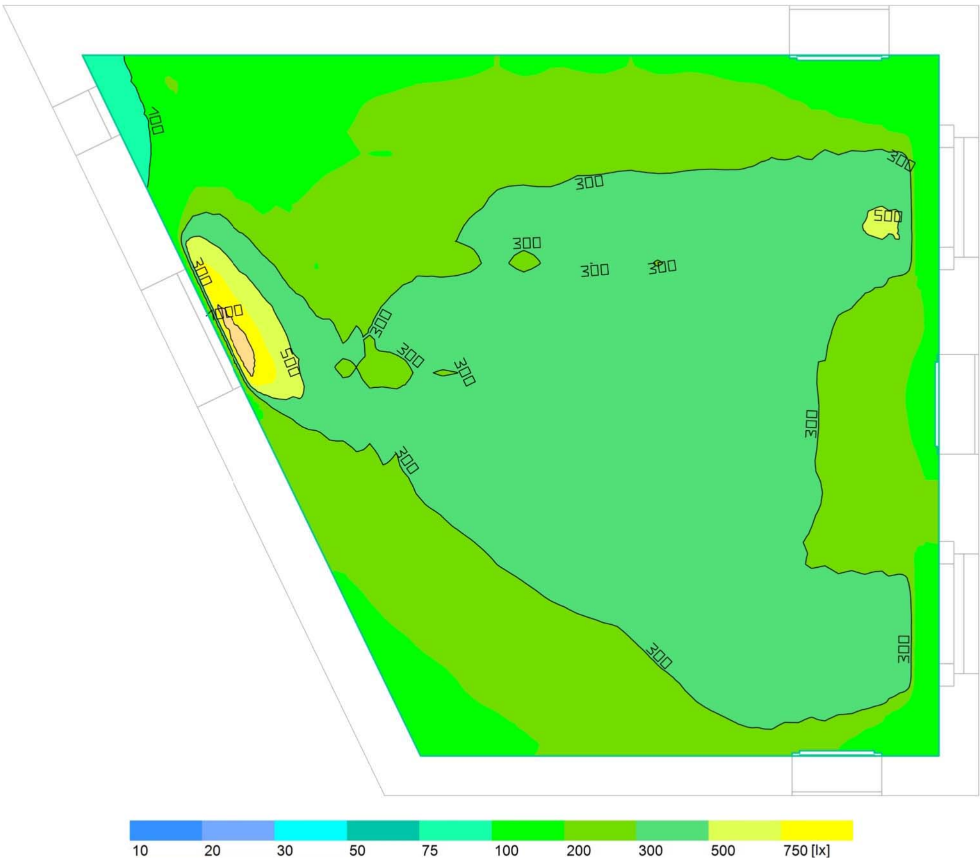


Figure 3.28: Isolux map of useful surface in Case D: $E_m = 290$ lx with $U_0 = 0.10$ at 0.80 m of height from the floor.

The classroom is located on the first floor, at an altitude of about 6 m, with two windows on via Marsala and two overlooking the portico of the internal courtyard of the building. The classroom receives more daylight than the previous ones but not enough to meet standard requirements ($\eta_m \geq 2\%$).

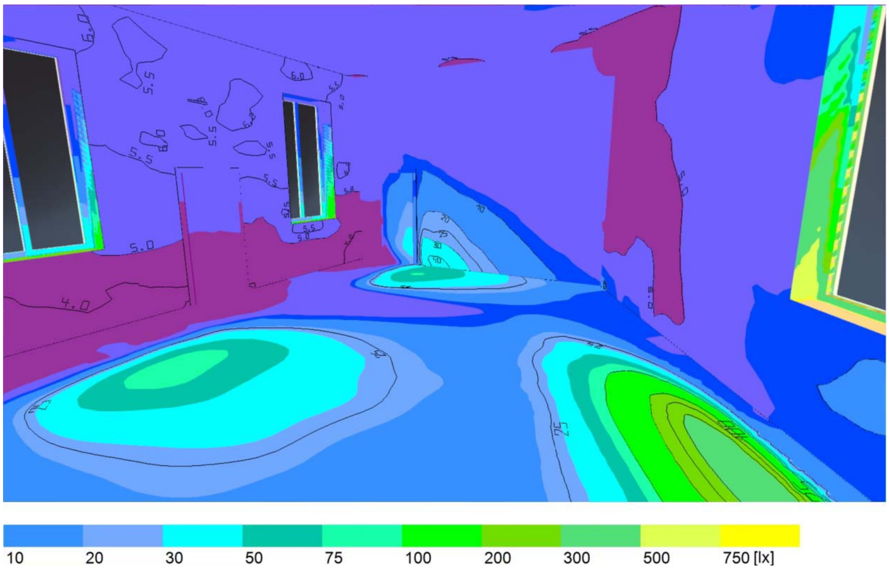


Figure 3.29: Daylight simulation results by Dialux in Case D.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.20	■

Table 3.19: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation without the software, the value of the average daylight factor has been calculated, considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}). Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.30) was calculated considering the frontal and facade obstruction.

For the two windows overlooking the internal courtyard:

Measure	Symbol	Value
Average reflection factor	r_m	0.57
Window area	A_f [m^2]	2.31
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	205
Window factor	ε	0.08

$$\eta_m = \frac{2 \cdot 2.31 \cdot 0.90 \cdot 0.08}{205 \cdot (1 - 0.57)} \cdot 0.90 = 0.003 \qquad (3.4)$$

For the large window overlooking Via Marsala, considering $A_f = 2.53$ m^2 and a window factor $\varepsilon = 0.15$ (3.30): $\eta_m = 0.003$
For the little window overlooking Via Marsala, considering $A_f = 0.36$ m^2 and a window factor $\varepsilon = 0.16$ (3.30): $\eta_m = 0.001$
So that the average daylight factor of the room is:

$$\eta_m = 0.003 + 0.003 + 0.001 = 0.007 \qquad (3.5)$$

The result is lower than that provided by the software: this is probably due to the fact that the rough calculation only considers the frontal obstruction, not all of the adjacent neighborhood and the reflections. Furthermore, the share of daylight is so variable that it will be difficult to find a result equal to that of the software.

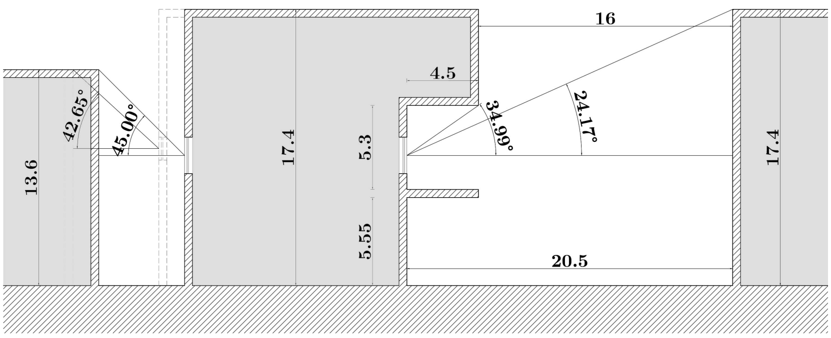


Figure 3.30: Angles considered for window factor in Case D.

Case E

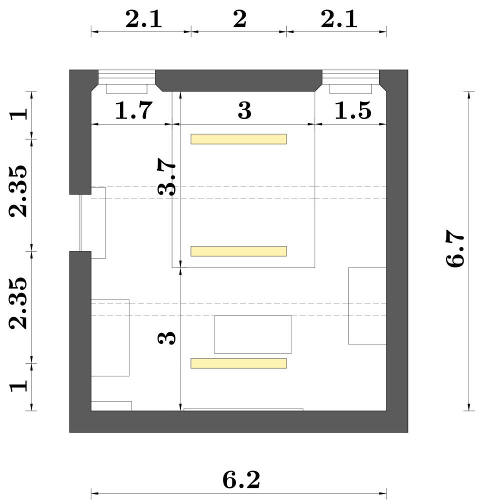


Figure 3.31: Case E plan; height of the luminaires at 3.60 m.

Small in size (200 m^3 with about 20 seats), it is located on the second floor in a position inside the building, exactly above Case C; it is almost square in size and with a flat ceiling with exposed beams. Plastered walls and cotto flooring, it has two windows facing a small internal service courtyard which are able to provide good daytime lighting; the seats are slightly padded with light colored reclining benches. Lighting is provided by suspended linear sources, placed parallel to the seating arrangement and generate direct light on the entire classroom surface.
The model used in the simulation was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting, considering 3 rectangular suspended lamps, fluorescent tube type, positioned at 3.60 m of height (fig. 3.33); colors and materials choosed for the simulation are represented in Tab. 3.20.

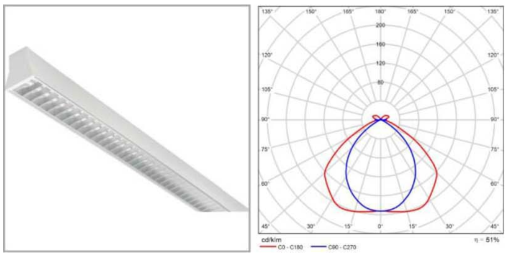
(a) Real photo of Case E.

(b) Dialux rendering of Case E.

Figure 3.32: Comparison between real photo and Dialux rendering, obtained reporting the same light conditions with both natural and artificial light, considering 3 rectangular suspended fluorescent lamps at 3.60 m of height.

Object	Colour/material	r
Walls	yellowish white	0.72
Ceiling	grey	0.18
Floor	cotto tile	0.15
Windows	soft green	0.32
Doors	white	0.75
Seats	blue fabric	0.07
Desks	white	0.86

Table 3.20: Case E: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.33: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case E: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

In this classroom the contribution of daylight is very important but despite this, considering also the artificial lighting with a 100% luminous flux, the minimum requirements for illuminance and uniformity are not satisfied [3]. Furthermore, the glare value is also very high and is probably due to the presence of exclusively direct lighting on the surface of the desks, with an incorrect arrangement of the luminaires, with the anti-glare plates in the wrong direction (fig. 3.34).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	158	0.73	20.2	■ (red)
	360	0.37	–	■ (red)
	285	0.18	–	■ (green)
Blackboard	98.5	0.81	27.6	■ (red)
	89.2	0.67	–	■ (red)
	239	0.21	–	■ (green)
Useful surface	292	0.15	–	■ (red)

Table 3.21: Case E: Dialux previsional evaluation for visual comfort.

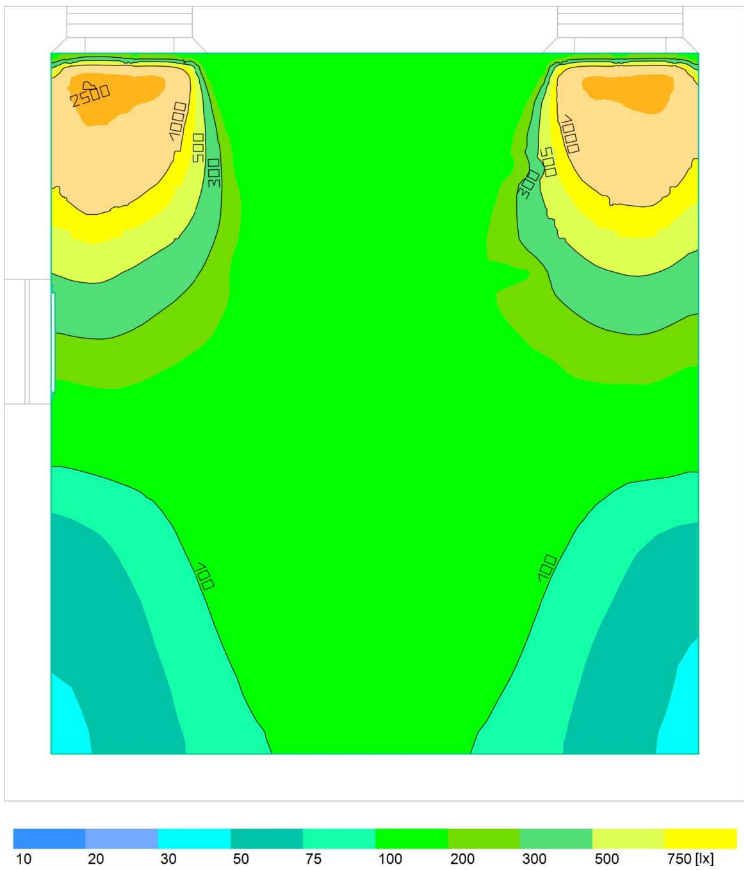


Figure 3.34: Isolux map of useful surface in Case E: $E_m = 290$ lx with $U_0 = 0.15$ at 0.80 m of height from the floor.

The premise is located on the second floor with two windows overlooking the same internal service courtyard of Case C. Being on the top floor, it receives an important amount of daylight capable of providing aid in lighting design. Despite this, the results provided by Dialux don't satisfy the minimum standard requirements.

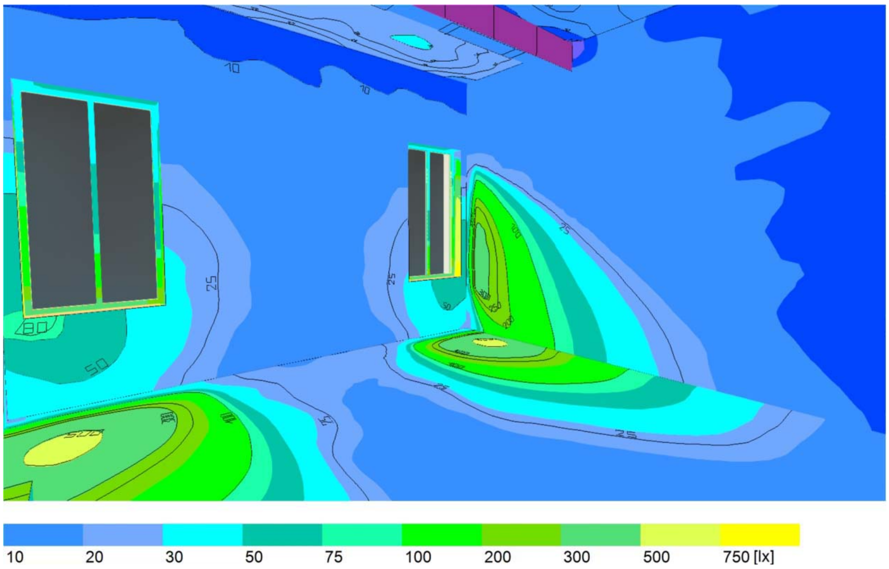


Figure 3.35: Daylight simulation results by Dialux in Case E.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.30	■

Table 3.22: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.36) was calculated

considering the frontal and facade obstruction ($\varepsilon = 0.24$). In this classroom the two windows are the same and have the same characteristics.

Measure	Symbol	Value
Average reflection factor	r_m	0.62
Window area	A_f [m^2]	2.52
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	200
Window factor	ε	0.24

Table 3.23: Case E parameters considered in daylight factor calculation.

$$\eta_m = \frac{2 \cdot 2.52 \cdot 0.90 \cdot 0.24}{200 \cdot (1 - 0.62)} \cdot 0.90 = 0.013 \tag{3.6}$$

As in Case D daylight calculation, the result is lower than that provided by the software. This confirms the above, that is, the calculation by hand is the line with a rough design while to obtain more sophisticated and closer to reality data it is necessary to use a calculation software like Dialux.

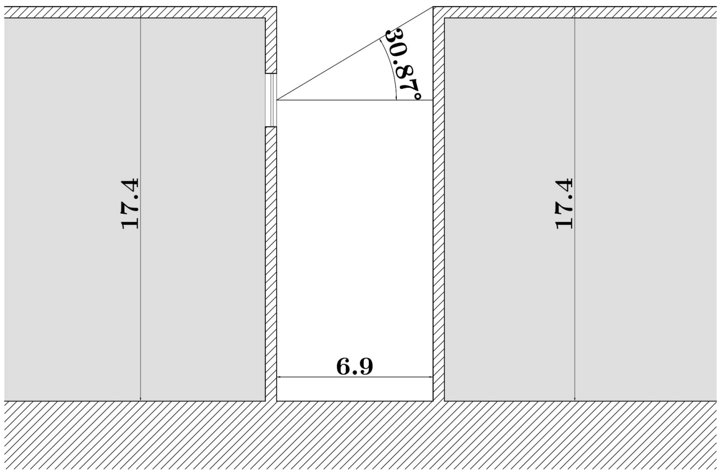
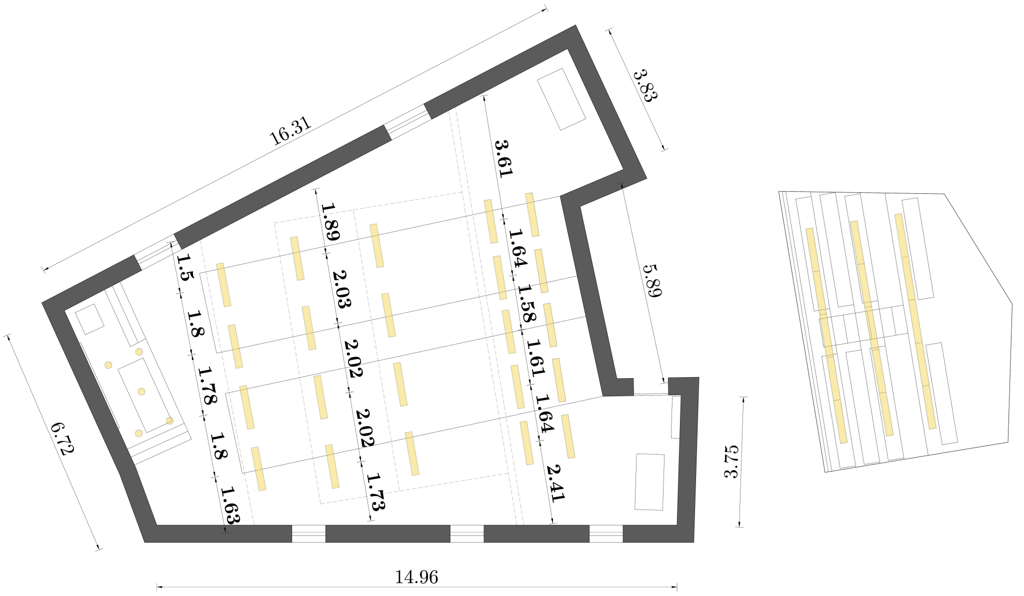


Figure 3.36: Angles considered for window factor in Case E.

Case F



(a) Plan of Case F ground floor.

(b) Plan of Case F mezzanine.

Figure 3.37: Case F plan: the premise has a false ceiling with steps and a mezzanine also with steps.

Large volume stretched in the direction of the stage, with windows on both long sides, towards the internal courtyard and towards the street (Via Marsala). It is divided into two volumes, the largest main one and an upper mezzanine which includes about a third of seats compared to those on the floor below. The walls are plastered while the ceiling has a geometry articulated on several flat levels which discretize the slope. The floor of the main floor is in cotto, while the mezzanine is entirely covered with linoleum, including steps. The capacity of the room is the largest of all the spaces of the building, while remaining smaller than other classrooms used for the same use in other faculties (about 120 seats). In the main volume, the lighting is mainly natural which is joined by rows of linear sources suspended from the false ceiling on several levels; in the mezzanine area lighting is provided exclusively by ceiling-mounted fixtures with linear sources, as well as in the relative area immediately below. In the stage area there are also tilting spotlights.

The model was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting, using suspended lamps (with a distance of 0.40 m from the ceiling) and surface mounted lamps, both fluorescent tube type (fig. 3.40); colors and materials choosed for the simulation are represented in Tab. 3.24.

(a) Real photo of the Case F.

(b) Dialux rendering of the Case F.

Figure 3.38: Comparison between real photo and Dialux rendering.

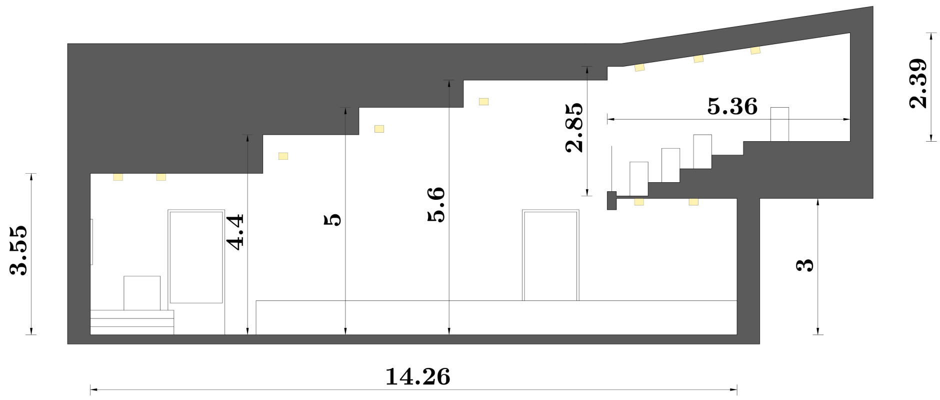
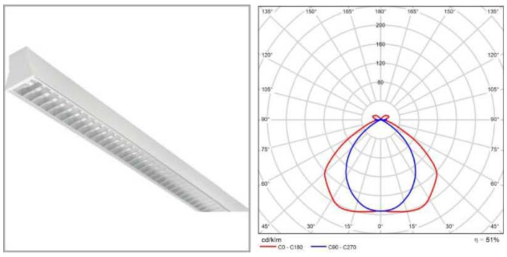


Figure 3.39: Section of Case F: the premise has a false ceiling with steps and a mezzanine also with steps.

Although the artificial lighting situation with 100% of outgoing luminous flux, despite the contribution of natural lighting, the minimum average illuminance value required by EN 12464-1 [3] is not reached (E_m on the useful surface at 0.80 m from the floor is 280 lux); moreover the distribution is exclusively direct and this causes non-uniformity illumination of the walls. In addition, the glare of visual tasks in some circumstances is excessive (UGR > 30): on the blackboard and on the seats in the mezzanine area and the one immediately below (fig. 3.42).

Object	Colour/material	r
Walls	yellowish white	0.86
Ceiling	yellowish white	0.86
Floor 1	cotto tile	0.10
Floor 2	linoleum	0.10
Windows	white	0.70
Seats 1	wood	0.26
Seats 2	grey	0.04
Desks	–	–

Table 3.24: Case F: Reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.40: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case F: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

Figure 3.41: Dialux render for an artificial lighting light scene with 100% emitted luminous flux.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Front desks	308	0.78	19.9	🟥
	352	0.66	–	🟩
	193	0.00	–	🟥
Back desks	453	0.71	17.2	🟧
	311	0.03	–	🟥
	191	0.00	–	🟥
Blackboard	263	0.77	> 30	🟥
	247	0.54	–	🟥
	196	0.00	–	🟥
Mezzanine	561	0.34	22	🟧
	478	0.01	–	🟥
	190	0.00	–	🟥
Useful surface	279	0.00	–	🟥

Table 3.25: Dialux previsional evaluation for visual comfort for an artificial lighting only light scene with 100% emitted luminous flux.

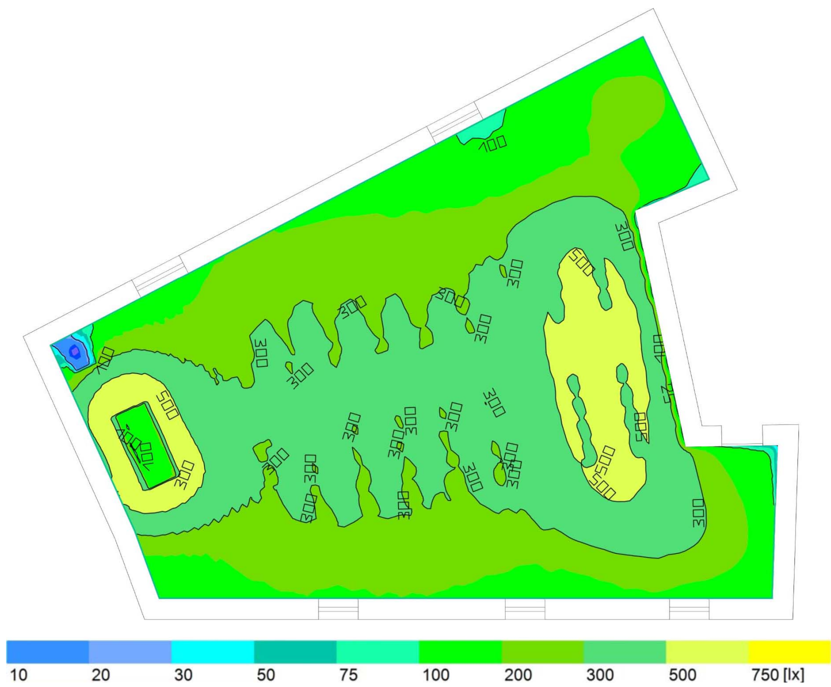


Figure 3.42: Isolux map of useful surface in Case F using only artificial lighting. E_m = 280 lx with U_0 = 0.01 at 0.80 m of height from the ground floor.

Being on the second floor and facing both sides, the daylight could be sufficient to meet regulatory requirements. However this is true for the areas adjacent to the window openings, certainly not in the mezzanine, which instead remains always in the dark if artificial lighting is off.

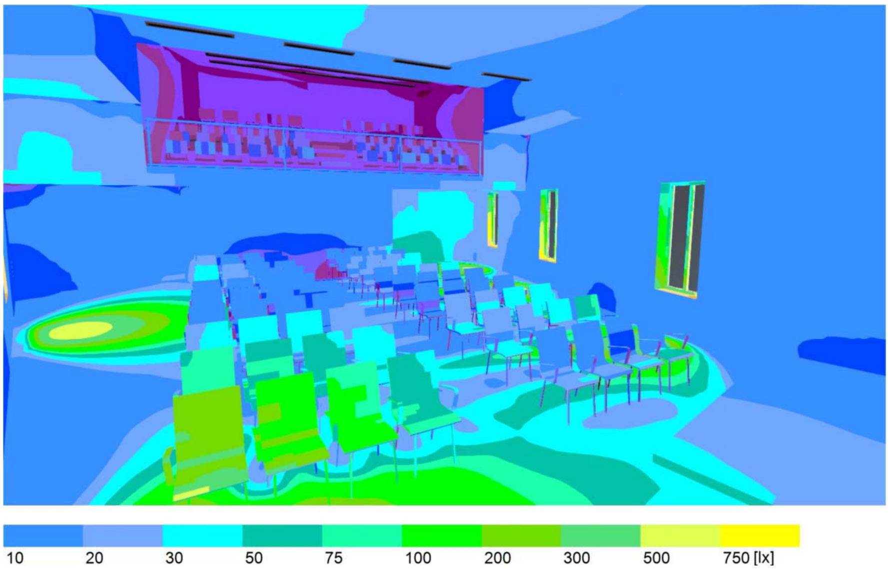


Figure 3.43: Daylight simulation results by Dialux in Case F.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.40	■

Table 3.26: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation without the software, the value of the average daylight factor has been calculated, considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}). Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.44) was calculated considering the frontal and facade obstruction.

For the three windows overlooking the internal courtyard:

Measure	Symbol	Value
Average reflection factor	r_m	0.58
Window area	A_f [m^2]	3.30
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	567
Window factor	ε	0.38

$$\eta_m = \frac{3 \cdot 3.30 \cdot 0.90 \cdot 0.38}{567 \cdot (1 - 0.58)} \cdot 0.90 = 0.013 \tag{3.7}$$

For the windows overlooking Via Marsala, considering $A_f = 4.56$ m^2 and a window factor $\varepsilon = 0.5$ (3.44): $\eta_m = 0.016$
So that the average daylight factor of the room is:

$$\eta_m = 0.013 + 0.016 = 0.029 \tag{3.8}$$

The result is lower than that provided by the software; however this is useful, especially in the design phase of existing buildings, to understand if the size and position of the windows is sufficient to guarantee a correct supply of natural light in the room.

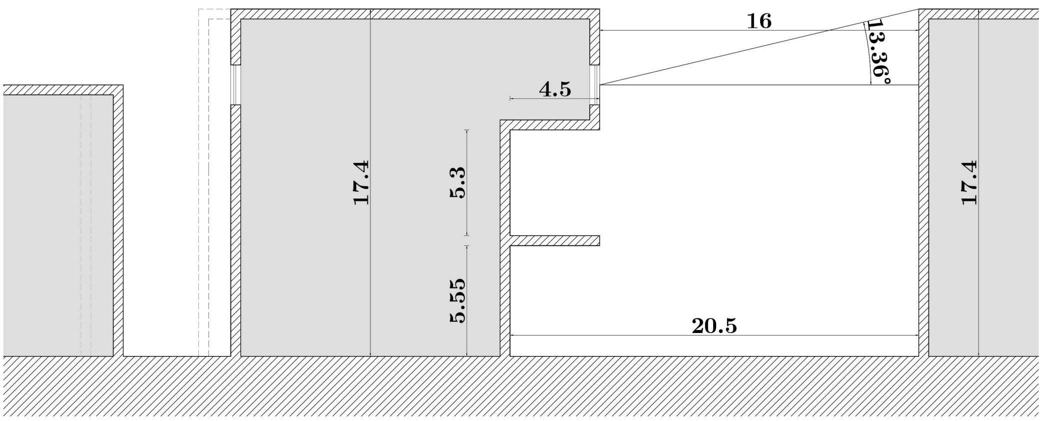


Figure 3.44: Angles considered for window factor in Case F.

Case G

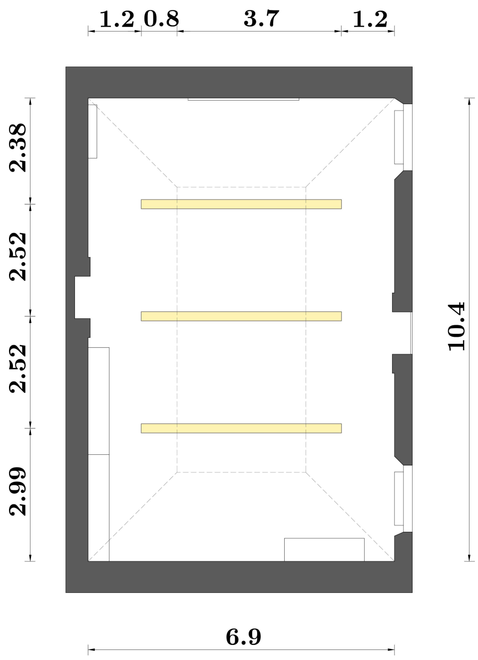


Figure 3.45: Case G plan; height of the luminaire at 3.80 m.

Medium in size for 370 m^3, Case G is located on the ground floor, overlooking the internal courtyard through two large windows. The walls are plastered and the flooring is in cotto; the ceiling is a pavilion vault, also plastered. Lighting is provided by linear suspended sources to which is added the contribution of natural light from the internal courtyard of Palazzo Malvezzi-Campeggi.
Inside there aren't desks or teaching tables but only some wooden furniture. Since there is no specific the visual task, in this room only the useful surface was considered, taking into account only the illuminance and uniformity parameters. The model was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting, using 6 suspended lamps, fluorescent tube type, at 3.80 m of height (fig. 3.47); colors and materials choosed for the simulation are represented in Tab. 3.27.

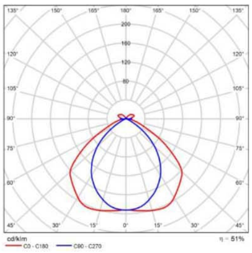
(a) Real photo of Case G.

(b) Dialux rendering of Case G.

Figure 3.46: Comparison between real photo and Dialux rendering.

Object	Colour/material	r
Walls	yellowish white	0.77
Ceiling	yellowish white	0.77
Floor	cotto tile	0.15
Windows	soft green	0.32
Doors	brown	0.08
Seats	–	–
Desks	–	–

Table 3.27: Case G: Surfaces reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.47: Rectangular suspended lamp with two fluorescent tubes considered in simulation of Case G: the photometric curve describes a direct light distribution and in the table the main parameters of the luminaire are present.

Despite the contribution of natural lighting, the minimum average illuminance value required by EN 12464-1 [3] is not reached (E_m on the useful surface at 0.80 m from the floor is 127 lux); moreover the distribution is exclusively direct and this causes non-uniformity illumination of the walls. Furthermore this type of distribution doesn't work both from an architectural point of view: the exclusively direct distribution of the luminous flux creates a non-uniformity of shadows on the walls, also clashing with the architectural typology of the ceiling (fig. 3.48).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Useful surface	127	0.10	–	■

Table 3.28: Dialux previsional evaluation for visual comfort.

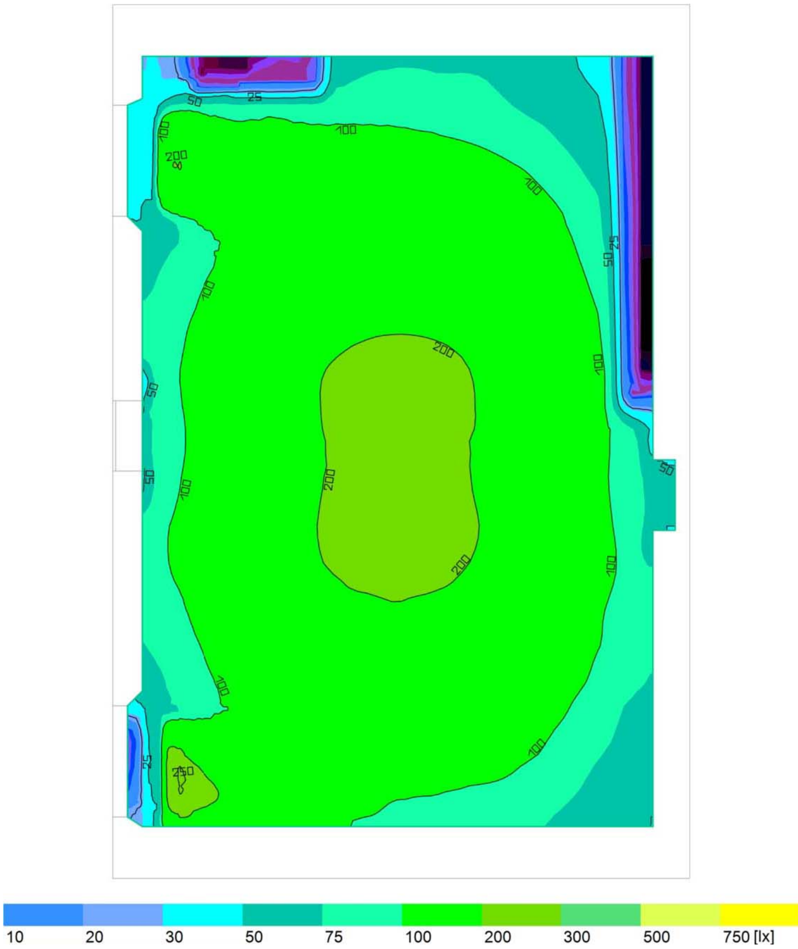


Figure 3.48: Isolux map of useful surface in Case G: $E_m = 130$ lx with $U_0 = 0.01$ at 0.80 m of height from the floor.

Being on the ground floor and facing the portico of the internal courtyard, with an average height of 6 m, the room in question receives a very low contribution of natural light, reaching average illuminance values of about 100 lux only in correspondence with the windows.

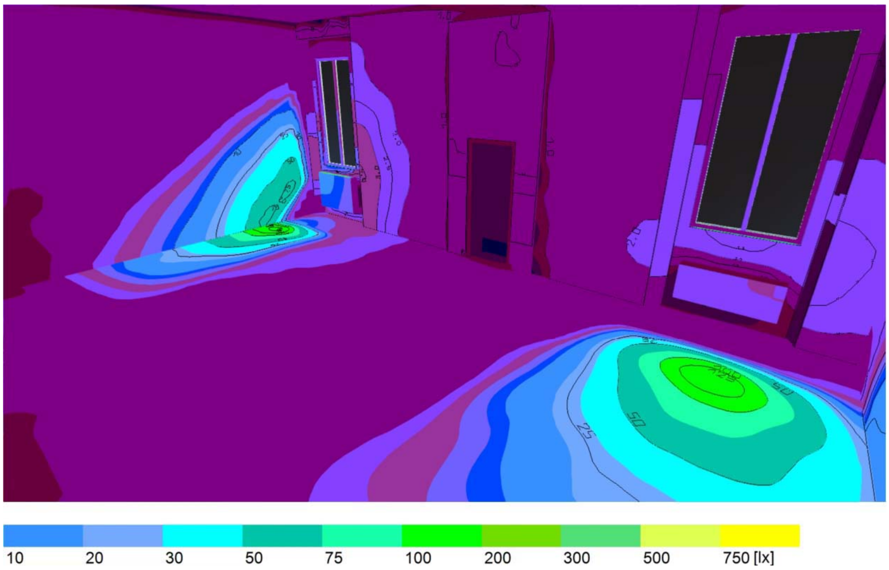


Figure 3.49: Daylight simulation results by Dialux in Case G.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.05	■

Table 3.29: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.50) was calculated

considering the frontal and facade obstruction ($\varepsilon = 0.01$). In this classroom the two windows are the same and have the same characteristics.

Measure	Symbol	Value
Average reflection factor	r_m	0.57
Window area	A_f [m^2]	2.40
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	323
Window factor	ε	0.01

Table 3.30: Case G parameters considered in daylight factor calculation.

$$\eta_m = \frac{2 \cdot 2.40 \cdot 0.90 \cdot 0.10}{323 \cdot (1 - 0.57)} \cdot 0.90 = 0.001 \tag{3.9}$$

The result is lower than that reported by the software but it does not differ much from the latter therefore it is confirmed that the quantity of natural light in the room is insufficient.

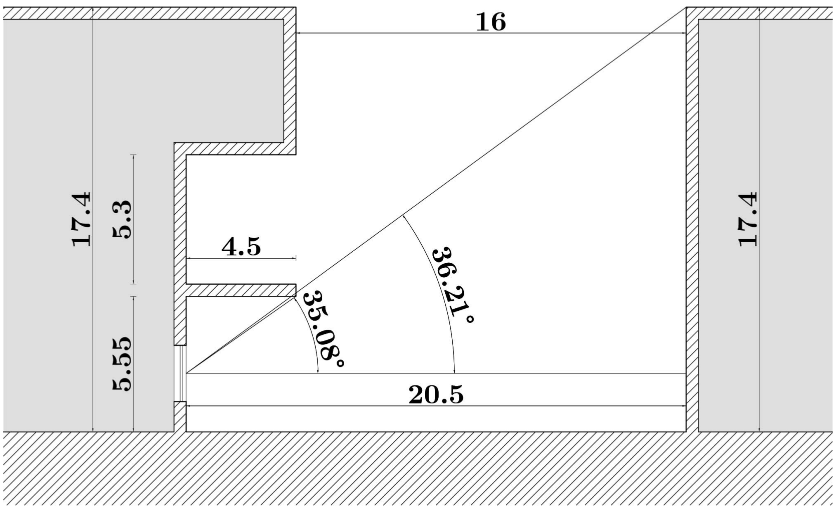


Figure 3.50: Angles considered for window factor in Case G.

Case H

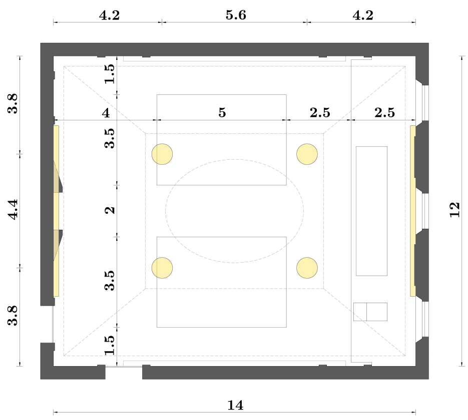


Figure 3.51: Case H plan; height of Taraxacum at 5.50 m.

One of the most prestigious rooms in the complex, used for graduation announcements and formal events. It consists of a large box-shaped volume (about 2000 m^3) embellished with stuccos and frescoes, in which an elaborate fake hearth stands out on which a sumptuous balcony is grafted which extends over the entire wall. The seats are padded, on a terracotta floor, with the exception of the stage area covered with carpet and illuminated by large windows on the Via Zamboni side. The vaulted ceiling joins an oval hole, also decorated, to a large volume above, with an oval crowning dome, illuminated by round windows. Lighting is mainly provided by the large windows; there are also 4 chandeliers similar to isotropic point sources. This large lecture room contains paintings by the landscape painter C. Lodi: for this surfaces it is advisable not to exceed 200 lux, being a relatively sensitive material; at most it is good not to exceed 600000 lux·h/year.
The model was calibrated for similitude with the photos, with both natural and artificial lighting, using the same model of the lamps present in reality (Taraxacum) and fluorescent tube lamps for indirect light (fig. 3.53); colors and materials choosed for the simulation are represented in Tab. 3.31.

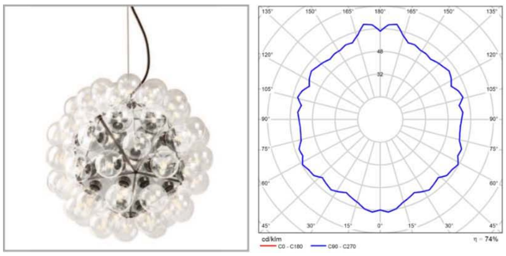
(a) Real photo of Case H.

(b) Dialux rendering of Case H.

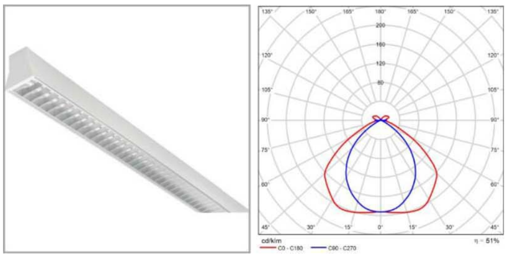
Figure 3.52: Comparison between real photo and Dialux rendering.

Object	Colour/material	r
Walls	greenish white	0.68
Ceiling	yellowish white	0.77
Floor	cotto tile	0.07
Stuccos	yellowish white	0.85
Seats	dark red	0.05
Doors	brown	0.19
Desks	–	–

Table 3.31: Case H: Reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.



Parameter	Value
P	1500 W
Φ_{lamp}	13200 lm
Luminous efficiency	6.5 lm/W
CCT	2688 K



Parameter	Value
P	76.0 W
$\Phi_{lightbulb}$	6600 lm
Φ_{lamp}	3345 lm
η	50.68 %
Luminous efficiency	44.0 lm/W
CCT	4033 K

Figure 3.53: Four suspended Taraxacum S1 designed by Achille Castiglioni for Flos and rectangular lamps with two fluorescent tubes, placed at the beginning of the vault, hidden by the stuccos: suspended lamps create diffuse lighting with very high luminous flux but low luminous efficienty; rectangular lamps, however, create indirect light.

In the room there are four Taraxacum chandeliers with a remarkable luminous flux compared to the actual lux on the various visual tasks. Furthermore, indirect artificial lighting does not provide a contribution that raises the illumination. The recommended values are respected on the paintings; uniformity is also good, as it is glare (fig. 3.54).

Task	E_m [lx]	U_0	UGR_{max}	Verified
Seats	120	0.87	< 10	■
	120	0.87	–	■
	92	0.69	–	■
Paintings	120	0.67	16.5	■
Useful surface	100	0.05	–	■

Table 3.32: Dialux previsional evaluation for visual comfort using only artificial lighting.

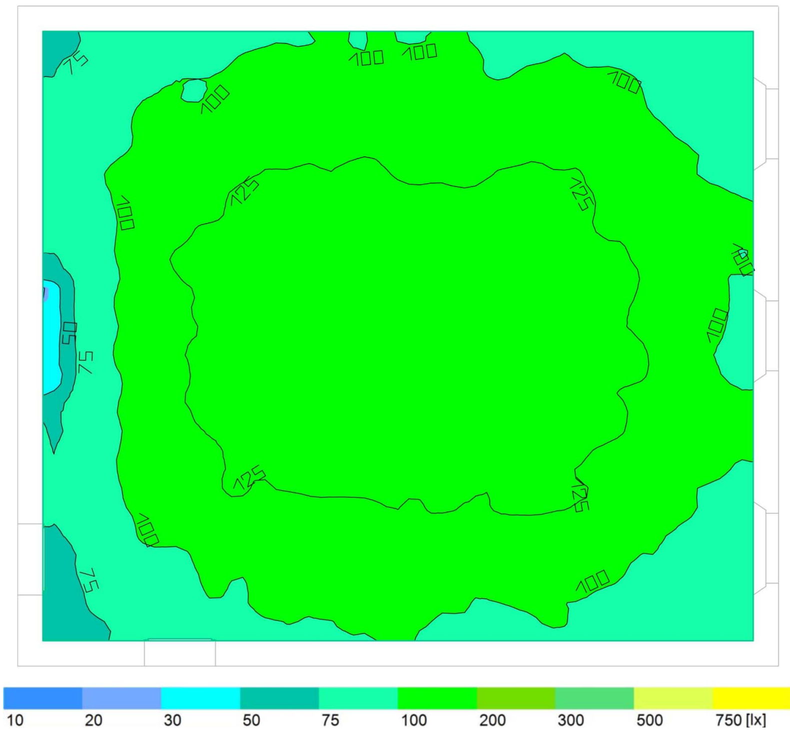


Figure 3.54: Isolux map of useful surface in Case H: $E_m = 115$ lx with $U_0 = 0.18$ at 0.80 m of height from the floor.

The premise is located on the first floor with three windows overlooking the Basilica of San Giacomo Maggiore. Thanks to the considerable size of the windows, it receives an important amount of daylight. Despite this, the results provided by Dialux do not satisfy the minimum standard requirements.

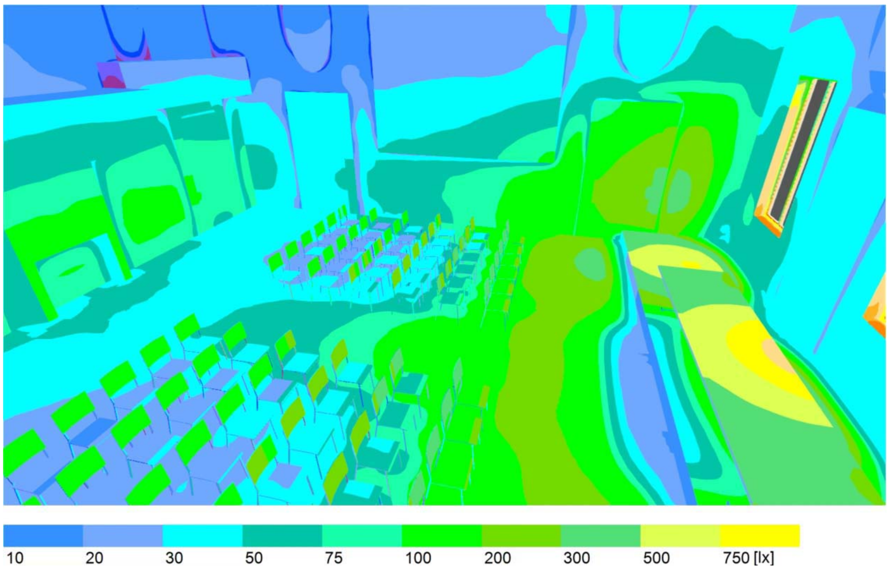


Figure 3.55: Daylight simulation results by Dialux in Case H.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.90	■

Table 3.33: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.56) was calculated

considering the frontal and facade obstruction ($\varepsilon = 0.14$). In this classroom the two windows are the same and have the same characteristics.

Measure	Symbol	Value
Average reflection factor	r_m	0.66
Window area	A_f [m^2]	3.44
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	1126
Window factor	ε	0.14

Table 3.34: Case H parameters considered in daylight factor calculation.

$$\eta_m = \frac{3 \cdot 3.44 \cdot 0.90 \cdot 0.14}{1126 \cdot (1 - 0.66)} \cdot 0.90 = 0.003 \tag{3.10}$$

The result is very much lower than that reported by the software probably because of the high semplification of the surfaces inside the room; therefore it is confirmed that the quantity of natural light in the room is insufficient.

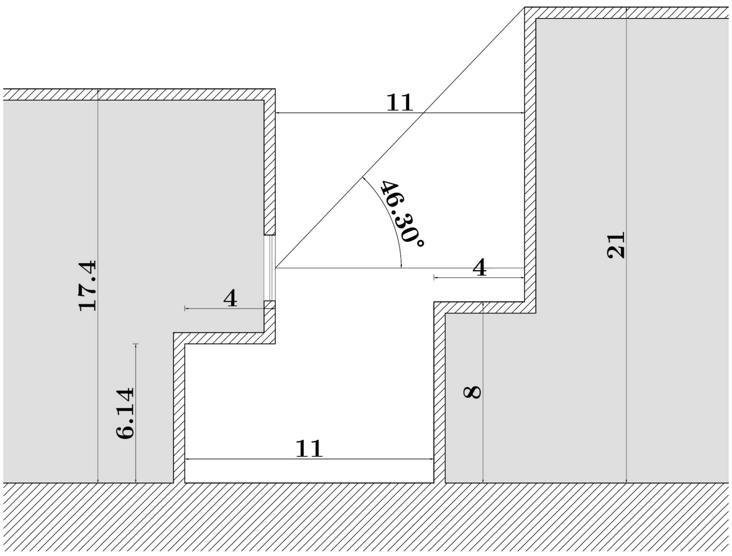


Figure 3.56: Angles considered for window factor in Case H.

Case I

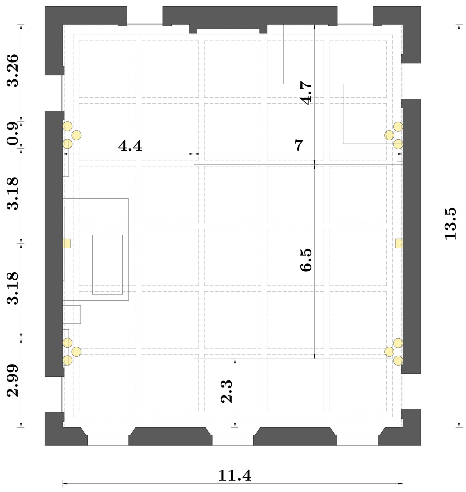


Figure 3.57: Case I plan; height of the luminaires at 3.80 m.

Another space of considerable value, presents the peculiar addition of a small transparent volume of mediation and L with a barrel vault, located in the corner of access from the courtyard. The ceiling is richly decorated with painted wooden drawers while the flooring is in terracotta, with the exception of the stage area covered with carpet; the seats are in wood with reclining light colored benches. The Hall has three large windows facing Via Zamboni which contribute to all the daytime lighting, together with three small square windows positioned above. The lighting is provided by 4 point sources mounted on the wall, each with three discharge lamps that emit at the frequencies of the green and a wall-mounted luminaire that provides both indirect and direct lighting on the desk level. Also in this case, the ceiling will be considered as relatively sensitive material so it is advisable not to exceed 200 lux.
The model was calibrated for similitude with the photos, reporting the same lighting conditions with both natural and artificial lighting; colors and materials choosed for the simulation are represented in Tab. 3.35.

(a) Real photo of Case I. (b) Dialux rendering of Case I.

Figure 3.58: Comparison between real photo and Dialux rendering.

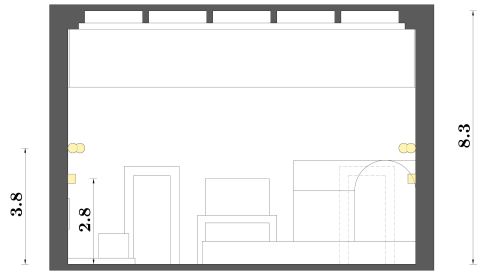
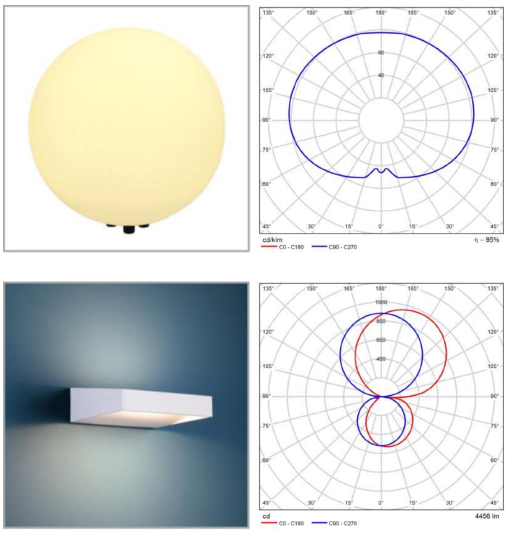


Figure 3.59: Section of Case I.



Parameter	Value
P	11.0 W
Φ_{lamp}	600 lm
Luminous efficiency	51.9 lm/W
CCT	3000 K

Parameter	Value
P	72.0 W
Φ_{lamp}	4456 lm
Luminous efficiency	61.9 lm/W
CCT	3000 K

Figure 3.60: Four point sources, each with three discharge lamps that emit at the frequencies of the green and two wall-mounted luminaire.

Object	Colour/material	r
Walls	yellowish white	0.77
Ceiling	painted	0.20
Floor	cotto tile	0.07
Stuccos	greyish	0.20
Seats	wood	0.26
Doors	greenish	0.32
Desks	white	0.86

Table 3.35: Case I: Reflection coefficients of the room choosed for similitude by photos in situ, using values recommended in the article by V. Costanzo et al. [37] and comparing them with the reflection coefficient from Dialux.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	36	0.41	> 30	■
	50	0.26	–	■
	58	0.01	–	■
Ceiling	23	0.14	> 30	■
Useful surface	64	0.05	–	■

Table 3.36: Dialux previsional evaluation for visual comfort using artificial and natural lighting.

Case I is dark and has very low uniformity, with areas sufficiently illuminated only in correspondence with lamps or windows. Lighting on desks is poor, as the coffered ceiling which is not given any prominence (fig. 3.61).

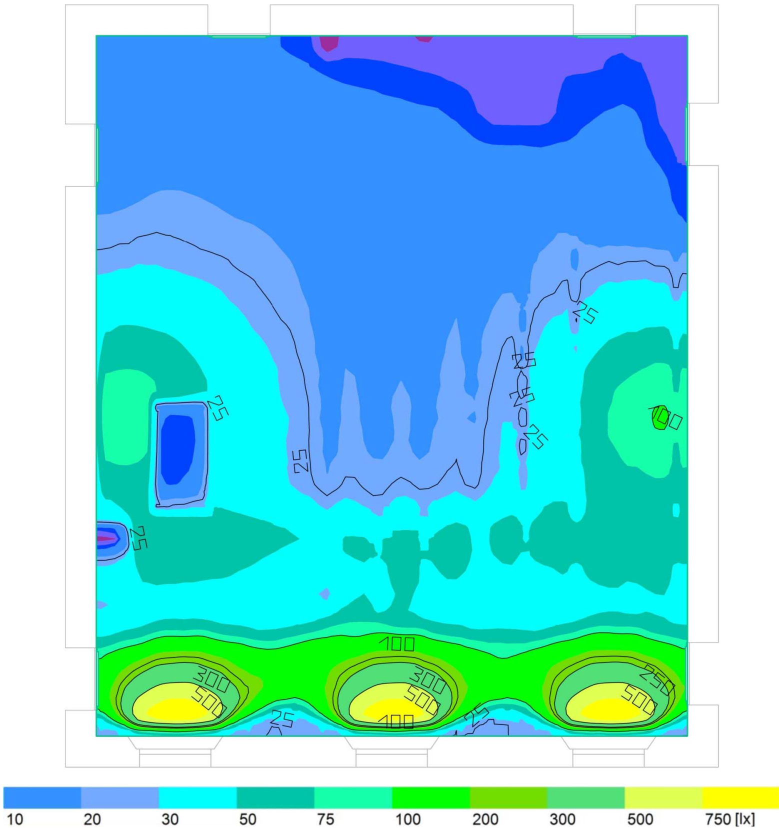


Figure 3.61: Isolux map of useful surface in Case I: $E_m = 60$ lx with $U_0 = 0.0.05$ at 0.80 m of height from the ground floor.

Also in this case the premise is located on the first floor with three windows overlooking the Basilica of San Giacomo Maggiore. Thanks to the considerable size of the windows, it could receive an important amount of daylight capable of providing aid in lighting design. Despite this, the results provided by Dialux don't satisfy the minimum standard requirements.

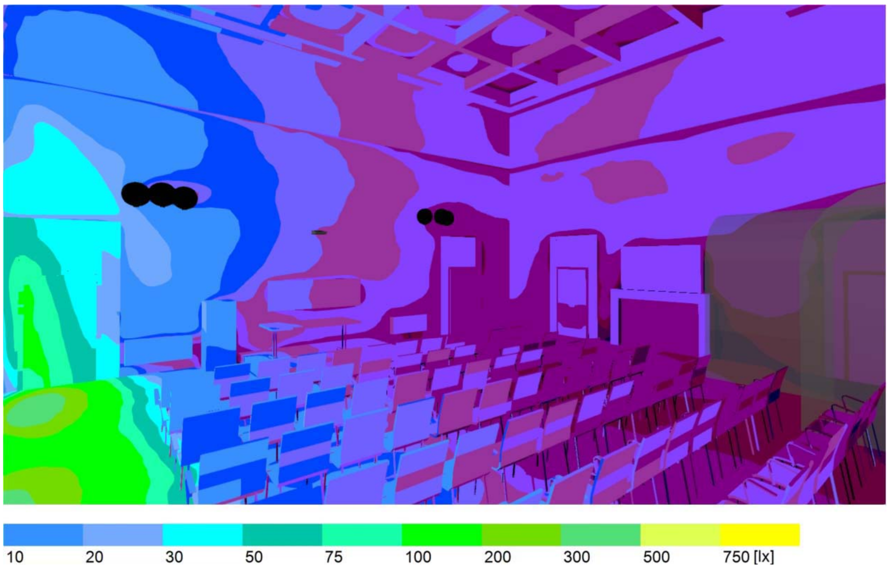


Figure 3.62: Daylight simulation results by Dialux in Case I.

Task	η_m [%]	Verified
Useful surface for daylight factor	0.90	■

Table 3.37: Dialux previsional evaluation for daylight factor, considering the presence of adjacent buildings and calculated in overcast conditions on 15 April at 12.00, intermediate period of school use.

For a preliminary calculation carried out in the absence of the software, which is certainly more sophisticated, the following parameters were considered. For each window, the value of the average daylight factor is calculated and the results obtained are added.
Considering the main classroom surfaces, such as walls, ceiling, floor and glass, the average reflection coefficient (r_m) and the global area (A_{tot}) were calculated. Taking into consideration a simple glass, a transmission factor $t = 0.90$ and a reduction factor $\psi = 0.90$ was used, calculated based on the size of the window. Finally, the window factor (Fig. 3.63) was calculated

considering the frontal and facade obstruction ($\varepsilon = 0.14$). In this classroom the two windows are the same and have the same characteristics.

Measure	Symbol	Value
Average reflection factor	r_m	0.40
Window area	A_f [m^2]	3.44
Transmission factor	t	0.90
Reduction factor	ψ	0.90
Global area	A_{tot} [m^2]	899
Window factor	ε	0.14

Table 3.38: Case I parameters considered in daylight factor calculation.

$$\eta_m = \frac{2 \cdot 3.44 \cdot 0.90 \cdot 0.14}{899 \cdot (1 - 0.40)} \cdot 0.90 = 0.002 \tag{3.11}$$

The result is lower than that reported by the software but it is confirmed that the quantity of natural light in the room is insufficient.

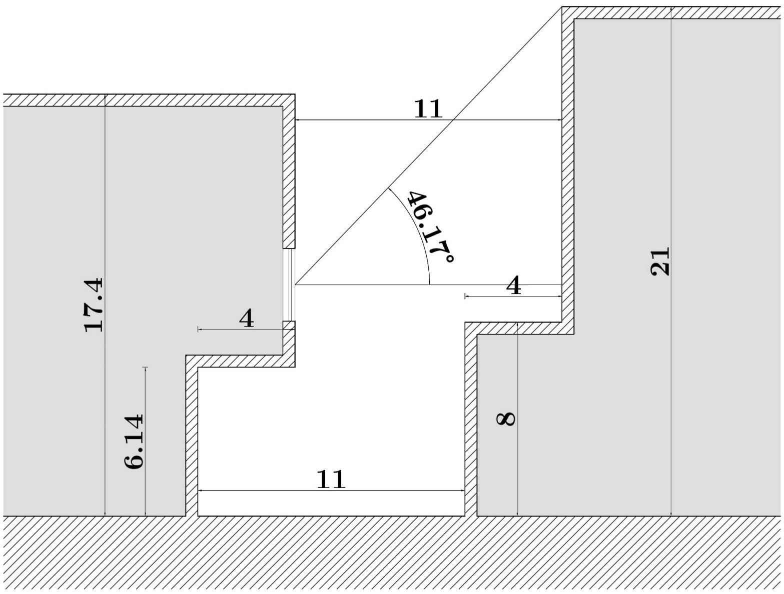


Figure 3.63: Angles considered for window factor in Case I.

Chapter 4

Lighting treatment and results

4.1 Method

This section illustrates the lighting design proposals for the classrooms of Palazzo Malvezzi-Campeggi obtained through simulations on Dialux; based on the parameters previously exposed, mainly following the EN 12464-1 [3], each class has been designed and tested with the aim of reducing energy consumption, replacing lamps and luminaires with new LED technologies.
The check was carried out in the first instance considering only artificial lighting, adding later also natural lighting, which despite being insufficient in some classrooms, is still present. Depending on the classroom, different light scenes were addressed depending on the daylight present.
Basically, in each simulation a maintenance factor of 0.80 has been set, taking into account that in CIE [5] the LLMF values for LED lights are not given as they change too quickly. Dialux as standard setting sets 0.80 as maintenance factor, which corresponds to a working environment in good cleaning conditions, with an ordinary reduction coefficient d = 1.25 (MF = 1/d).
Thanks to the participation in an integrated project with acoustics, not discussed here, a new lighting system has been created for the previously illustrated case studies. For the project, the needs of both parties were taken into account, such as choosing the right reflection coefficient for the acoustic panels or positioning them so that they were an active part of the integrated system. The aim of the whole design proposal was to respect the existing, especially in the rooms of greater historical value, subjected to an architectural constraint, however trying to make the environment functional for the purpose of the university classroom.
To obtain improvements also from the point of view of energy efficiency, it was preferred to use LED devices, as they constitute an advantage in the

medium and long term, leading to large savings already a few months after their purchase. Unlike other energy-saving systems such as the use of fluorescent lamps, they do not contain dangerous gases such as mercury vapors, have a significantly longer life span and have even lower consumption. Compared to old incandescent and halogen technologies, LED lamps allow energy savings of between 70 and 90% in light output and they do not heat by not emitting infrared rays and do not constitute a danger by not emitting harmful UV rays.

For a better design than the current one, the profile for auditorium was chosen as the usage profile. In this way, an average illuminance of at least 500 lux was guaranteed on the visual task with minimum uniformity of 0.60 and maximum glare of 19 (Tab. 3.2 and Tab. 3.3). In addition to these, which are the main parameters, the cylindrical illuminance parameter was also verified as it is also necessary to highlight objects and surface textures and improve the visibility of people in space, allowing good communication and recognition of objects and shapes. To verify the correct lighting distribution between direct and indirect light, modeling was also taken into consideration, which must have a value between 0.30 and 0.60.

All verifications of the main parameters were carried out in the worst case, with the presence of only artificial lighting. In this way, by using dimmable luminaires, it will be possible to lower the luminous flux of the luminaires according to the amount of daylight present in the room at a certain time of the day.

Various configurations have been supposed for each lecture hall, initially using the current positions of the luminaires; subsequently, depending on the results and the situation, different distributions were considered, which best interacted with the acoustic component and with the necessary precautions in order not to exceed the glare.

4.2 Lighting design proposals

Case A

In this classroom it was decided to reposition the lighting fixtures perpendicular to the actual state, in order to prevent too high glare. In this way it was possible to interact with the acoustic component, which provides hanging baffles and a wall-mounted panel, similar in color to the walls, exploiting their reflection thus creating a well-lit environment for indirect reflection. However, it was also useful to use direct lighting component to evaluate illuminance on desks so the design solution considers direct and indirect luminaires, with dimmable LEDs, suspended on tie rods.

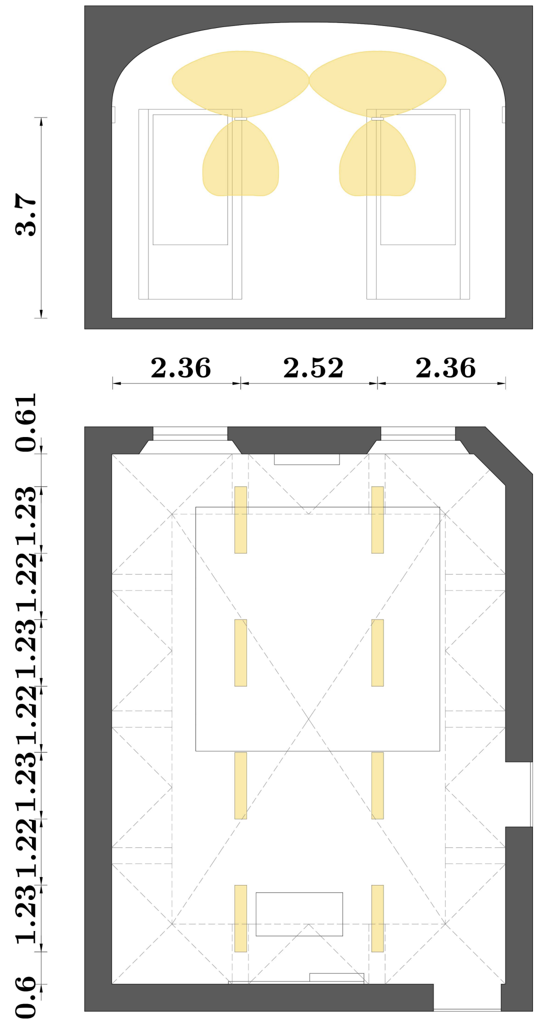
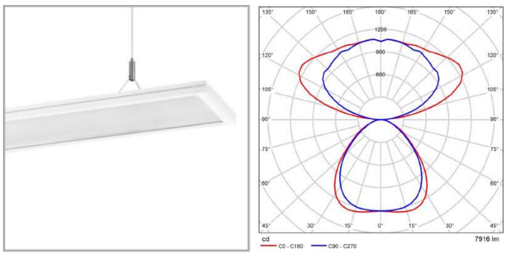


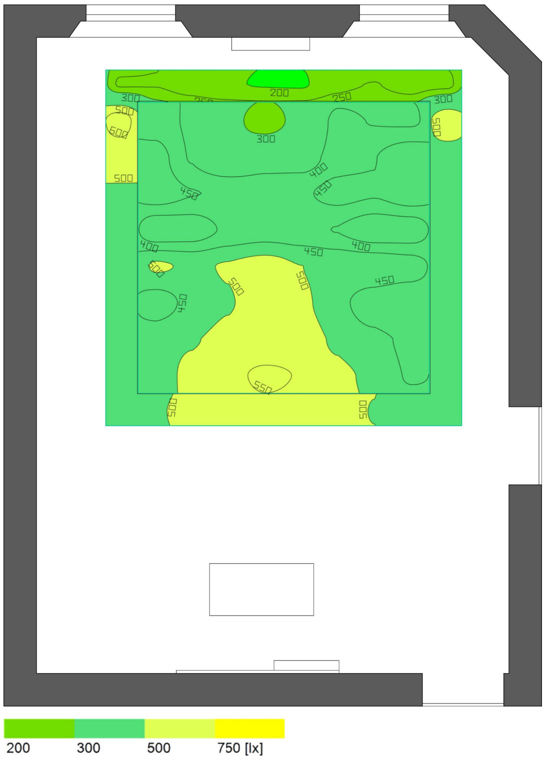
Figure 4.1: Project section and plan in Case A.

Figure 4.2: Case A rendering by Dialux in a situation with all lights ON, except for back luminaires that are OFF, considering natural lighting too. In the figure are also present acoustic baffles, well integrated with the new lighting system.

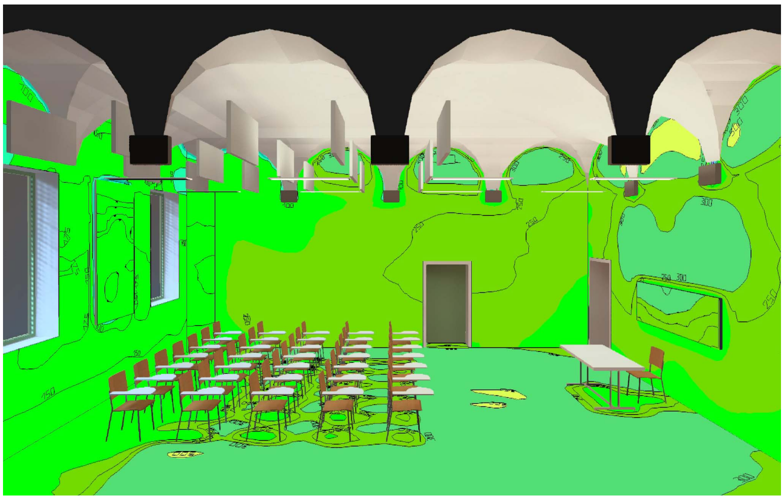


Parameter	Value
P	67.0 W
Φ_{lamp}	7906 lm
Luminous efficiency	118.0 lm/W
CCT	4000 K

Figure 4.3: Luminaires used in Case A: direct and indirect luminaires, with dimmable LEDs, suspended on tie rods. There are two rows of four elements, for a total of eight luminaires.



(a) Isolux map of desks in Case A: $E_m = 450$ lx, $U_0 = 0.60$.



(b) Dialux rendering of Case A with isolux curves and colours on main surfaces.

Figure 4.4: Simulation results by Dialux in Case A for a situation with all lights ON, except for back luminaires that are OFF, considering natural lighting too. The figures show a correct distribution of illuminance on floor and walls and a well-balanced illuminance on desks that receive direct light from luminaires and indirect light by reflections.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	500	0.80	13.2	■
	450	0.70	–	■
	380	0.60	–	■
Blackboard	320	0.95	15.4	■
	300	0.80	–	■
	340	0.60	–	■
Useful surface	470	0.50	–	■

Table 4.1: Dialux previsional evaluation for visual comfort in Case A for a light scene with all lights ON and without natural light. This is the worse situation and the results are good. So in a normal situation, with natural light too, luminaires can be switched off or at the 50% of their luminous flux.

Measure	Value	U_0	Verified
M	0.40	–	■
E_0 [lx]	570	0.80	■
E_z [lx]	250	0.85	■

Table 4.2: Dialux previsional evaluation for desks lighting modelling in Case A. The results show a good distribution between direct and indirect light and light that reaches the students is good to evaluate the visibility of objects and the other people inside the room.

Case B

In this case, being correct the positioning of the current fixtures, it was decided to exploit these positions and the same lighting type. The acoustic component, as in the previous case, includes hanging baffles and a wall-mounted panel of the same light color as the walls and ceiling, in order to exploit their reflection and contribute to the diffusion of light in the space. Therefore, ceiling lights were used, mounted on the wall and slightly inclined, in order to bring the light beam upwards and provide correct illumination of the environment thanks to the reflections.

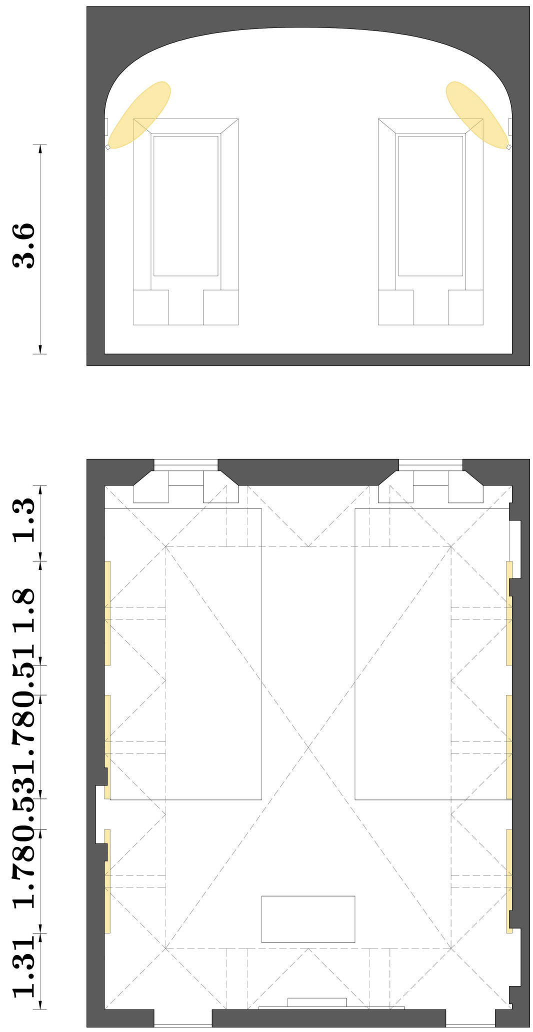
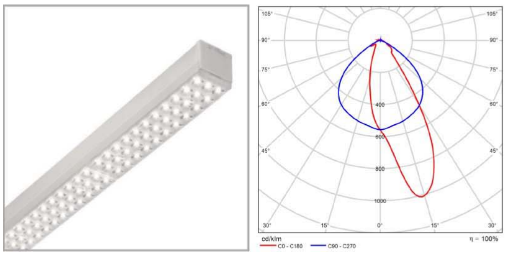


Figure 4.5: Project section and plan in Case B.

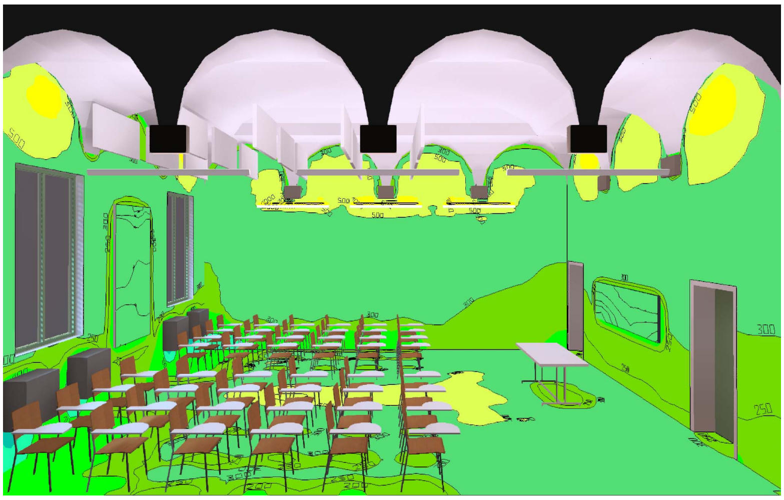
Figure 4.6: Case B rendering by Dialux in a situation with all lights ON, except for back luminaires that are OFF, considering natural lighting too. In the figure are also present acoustic baffles, well integrated with the new lighting system.



Parameter	Value
P	94.0 W
$\Phi_{lightbulb}$	14130 lm
Φ_{lamp}	14130 lm
η	100.00 %
Luminous efficiency	150.3 lm/W
CCT	4000 K

Figure 4.7: Luminaires used in Case B: indirect luminaires, with dimmable LEDs, wall-mounted. There are two rows of three elements, for a total of six luminaires.

(a) Isolux map of desks in Case B: $E_m = 470$ lx, $U_0 = 0.60$.



(b) Dialux rendering of Case B with isolux curves and colours on main surfaces.

Figure 4.8: Simulation results by Dialux in Case B for a situation with all lights ON, except for back luminaires that are on 50%, considering natural lighting too. The figures show a correct distribution of illuminance on floor and walls and a well-balanced illuminance on desks that receive only indirect light by reflections.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	430	0.70	17.6	🟧
	430	0.40	–	🟩
	330	0.20	–	🟩
Blackboard	330	0.90	15.0	🟧
	320	0.80	–	🟩
	320	0.40	–	🟩
Useful surface	460	0.10	–	🟧

Table 4.3: Dialux previsional evaluation for visual comfort in Case B for a light scene with all lights ON and without natural light. This is the worse situation and the results are good. So in a normal situation, with natural light too, luminaires can be switched off or at the 50% of their luminous flux.

Measure	Value	U_0	Verified
M	0.50	–	🟩
E_0 [lx]	500	0.70	🟩
E_z [lx]	250	0.80	🟩

Table 4.4: Dialux previsional evaluation for desks lighting modelling in Case B. The results show a good distribution between direct and indirect light and light that reaches the students is good to evaluate the visibility of objects and the other people inside the room.

Case C

Since the classroom was already bright enough, it was decided to reposition luminaires of the same type: four linear ceiling lights and four small rotatable wall lights, both types with dimmable LEDs. The acoustic component includes the insertion of a panel suspended on the vault and two wall panels, all in the same color as the walls and ceiling, able to integrate and contribute to the lighting system thanks to their high coefficient of light reflection.

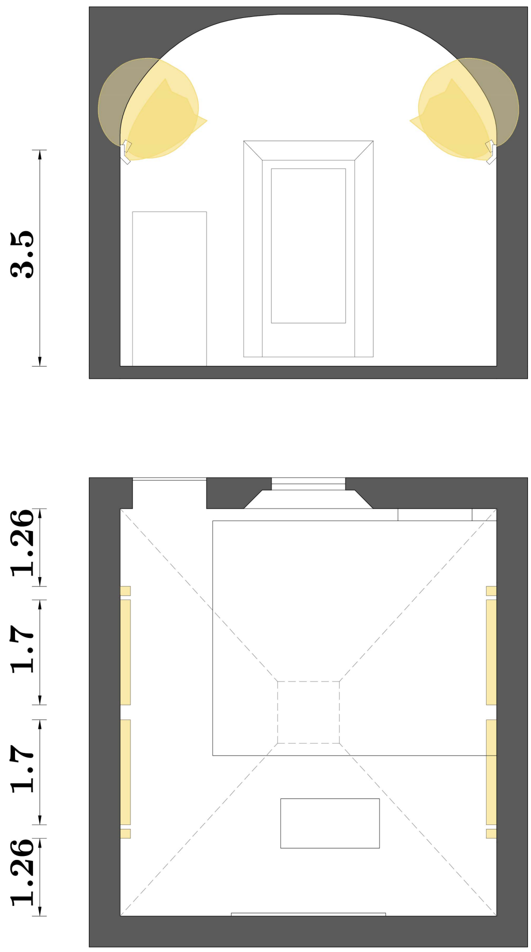
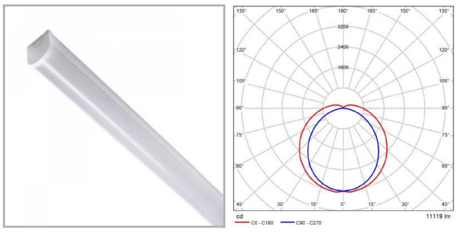
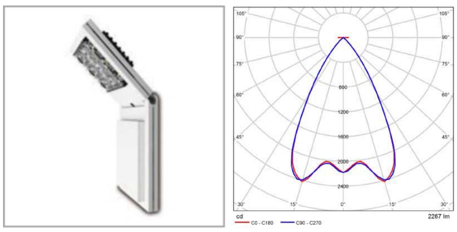


Figure 4.9: Project section and plan in Case C.

Figure 4.10: Case C rendering by Dialux in a situation with all lights ON, without daylight because in this room there is not contribution of natural lighting. In the figure are also present acoustic panels, well integrated with the new lighting system.

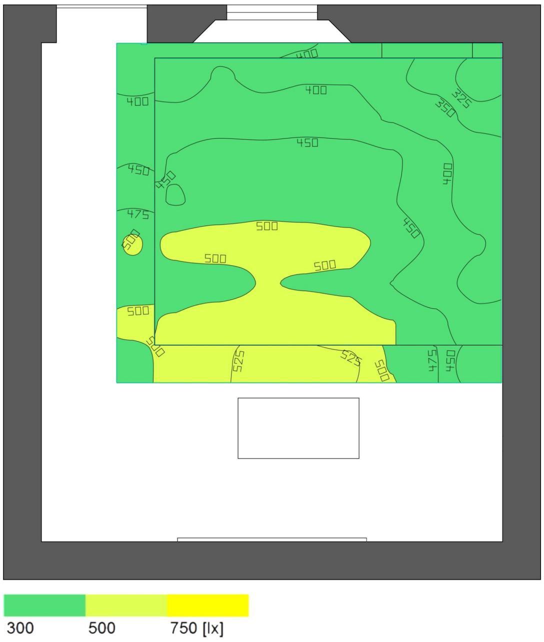


Parameter	Value
P	86.0 W
Φ_{lamp}	11119 lm
Luminous efficiency	129.3 lm/W
CCT	3783 K



Parameter	Value
P	21.0 W
Φ_{lamp}	2265 lm
Luminous efficiency	107.9 lm/W
CCT	4000 K

Figure 4.11: Luminaires used in Case C: indirect luminaires, with dimmable LEDs, wall-mounted. For total, four elements of each type of luminaire are present.



(a) Isolux map of desks in Case C: $E_m = 450$ lx, $U_0 = 0.70$.

(b) Dialux rendering of Case C with isolux curves and colours on main surfaces.

Figure 4.12: Simulation results by Dialux in Case C for a situation with all lights ON. The figures show a correct distribution of illuminance on floor and walls and a well-balanced illuminance on desks that receive only indirect light by reflections.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	450	0.70	15.9	■ (orange)
	480	0.80	–	■ (green)
	340	0.65	–	■ (green)
Blackboard	350	0.90	16.7	■ (orange)
	340	0.75	–	■ (green)
	290	0.50	–	■ (green)
Useful surface	450	0.60	–	■ (orange)

Table 4.5: Dialux previsional evaluation for visual comfort in Case C for a light scene with all lights ON. This is the worse situation and the results are good. So in a normal situation, also with a low contribution of natural light too, luminaires can be switched at the 50% or more of their luminous flux.

Measure	Value	U_0	Verified
M	0.50	–	■ (green)
E_0 [lx]	530	0.70	■ (green)
E_z [lx]	250	0.80	■ (green)

Table 4.6: Dialux previsional evaluation for desks lighting modelling in Case C. The results show a good distribution between direct and indirect light and light that reaches the students is good to evaluate the visibility of objects and the other people inside the room.

Case D

In the room in question the acoustic component involved the insertion of a wall panel, on the larger side, of the same color of the walls. The design project provides for the repositioning of the luminaires in such a way to guarantee sufficient illuminance even in the worst conditions of artificial lighting only. Suspended lamps were used, with dimmable LEDs, with direct and indirect lighting, the same udes also in Case A. It was preferred to position the luminaires as in the current state in order to take advantage of their mounting conditions.

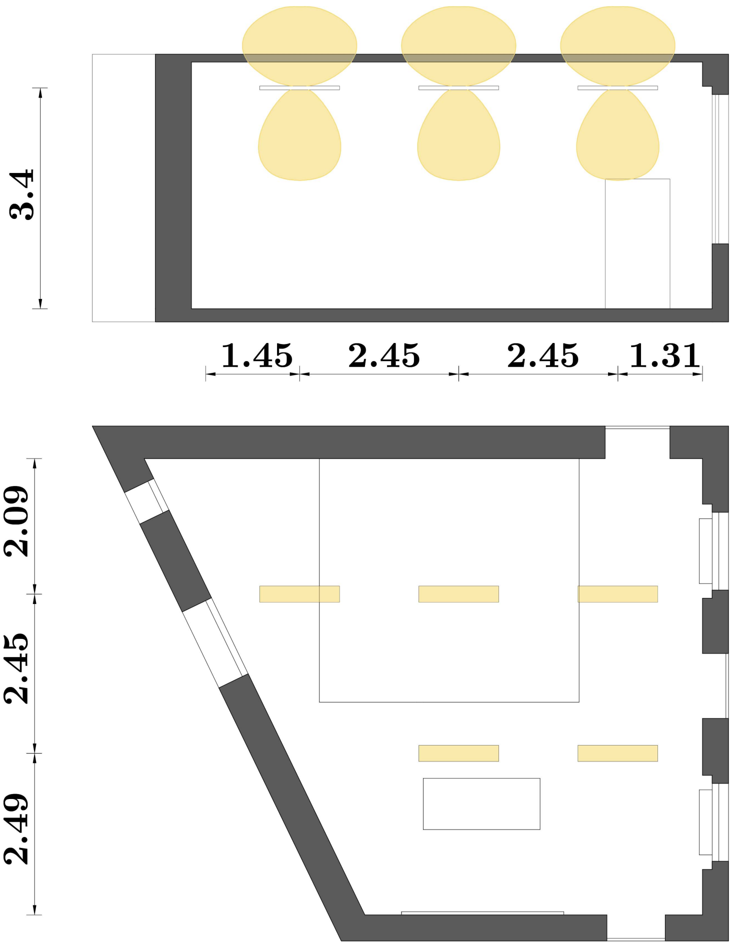
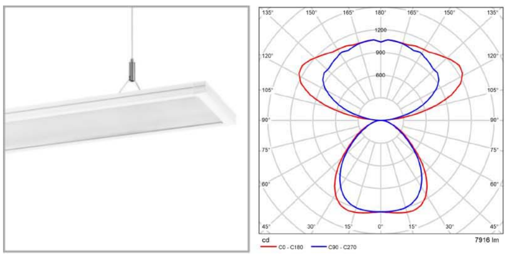


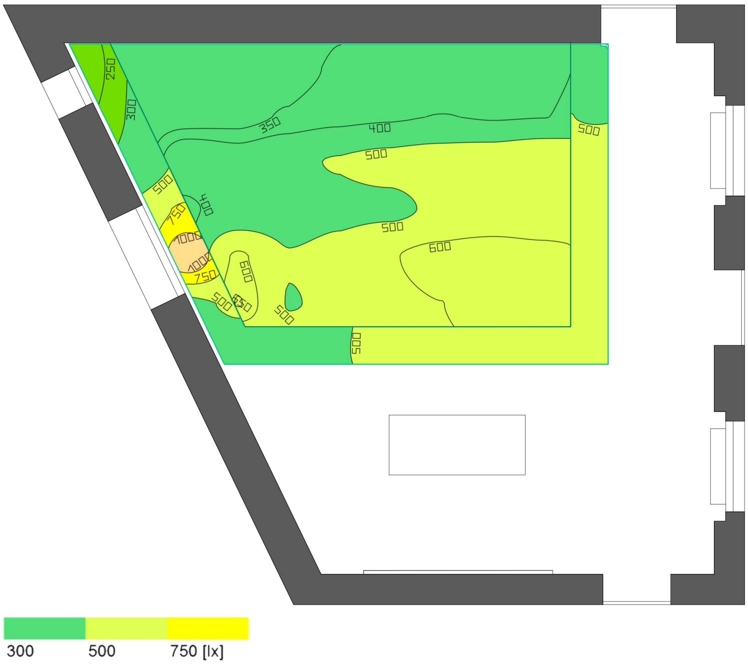
Figure 4.13: Project section and plan in Case D.

Figure 4.14: Case D rendering by Dialux in a situation with all lights ON, considering natural lighting too from both sides of the premise.

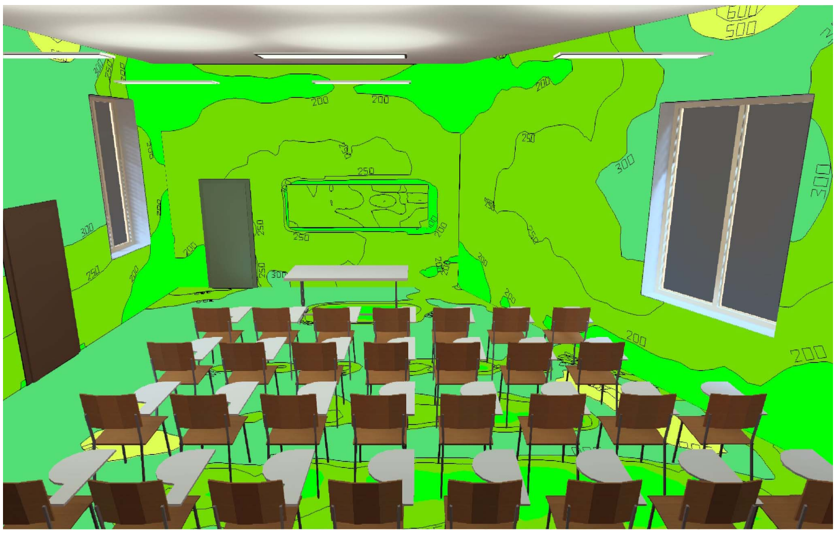


Parameter	Value
P	67.0 W
Φ_{lamp}	7906 lm
Luminous efficiency	118.0 lm/W
CCT	4000 K

Figure 4.15: Luminaires used in Case D: direct and indirect luminaires, with dimmable LEDs, suspended. There are two rows of elements, for a total of five luminaires.



(a) Isolux map of desks in Case D: $E_m = 480$ lx, $U_0 = 0.65$.



(b) Dialux rendering of Case D with isolux curves and colours on main surfaces.

Figure 4.16: Simulation results by Dialux in Case D for a situation with all lights ON, with the contribution of daylight from all the windows. The figures show a correct distribution of illuminance on floor and walls and a well-balanced illuminance on desks that receive only indirect light by reflections.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	450	0.60	13.2	🟧
	460	0.45	–	🟩
	340	0.40	–	🟩
Blackboard	270	0.90	< 10	🟧
	250	0.85	–	🟧
	300	0.45	–	🟩
Useful surface	450	0.20	–	🟧

Table 4.7: Dialux previsional evaluation for visual comfort in Case D for a light scene with all lights ON. This is the worse situation and the results are good. So in a normal situation, also with a low contribution of natural light too, luminaires can be switched at the 50% or more of their luminous flux.

Measure	Value	U_0	Verified
M	0.45	–	🟩
E_0 [lx]	520	0.50	🟩
E_z [lx]	220	0.80	🟩

Table 4.8: Dialux previsional evaluation for desks lighting modelling in Case D. The results show a good distribution between direct and indirect light and light that reaches the students is good to evaluate the visibility of objects and the other people inside the room.

Case E

Considering the worst lighting condition, without daylight, it was initially thought to reposition better-performing fixtures in the same position as in the current state. However this arrangement created an excessive glare both on the desks and on the blackboard. It was therefore decided to use the same devices in Case A and D by positioning them parallel to the visual beam. Also in this case the lamps are dimmable therefore in positive conditions from the daylight point of view it is possible to turn them off or in any case lower their outgoing luminous flux.

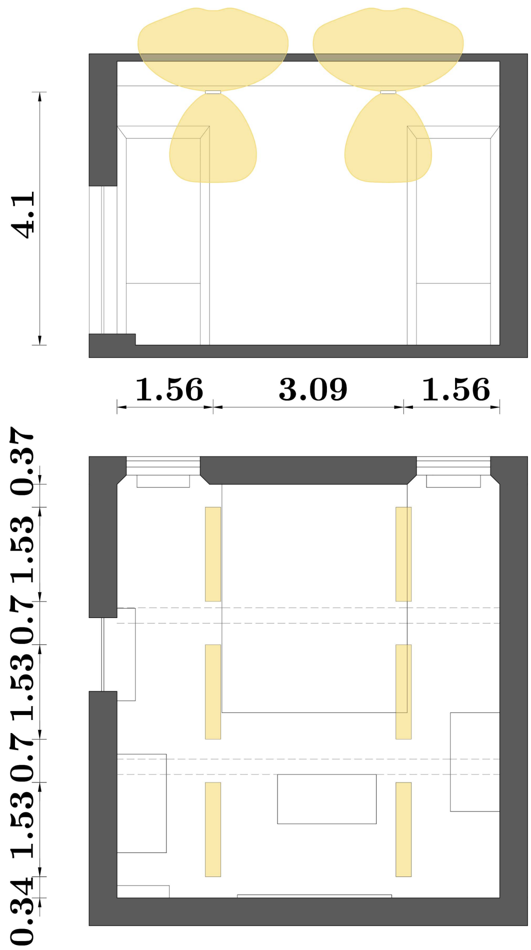
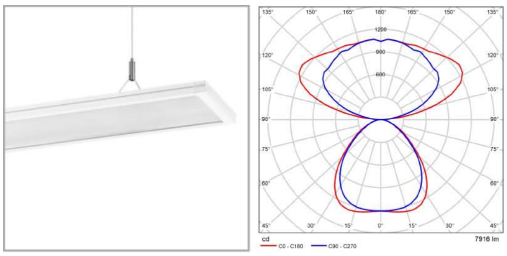


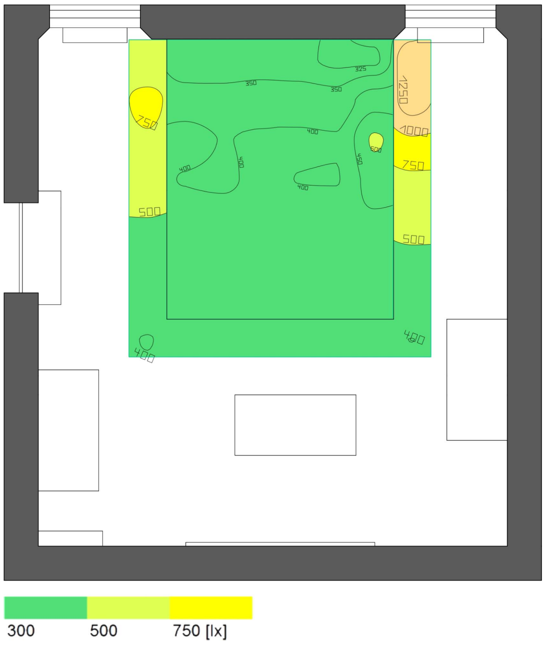
Figure 4.17: Project section and plan in Case E.

Figure 4.18: Case E rendering by Dialux in a situation with all lights ON, except for back luminaires that are on 50% of their luminous flux, considering natural lighting too. In the figure are also present suspended acoustic panels, well integrated with the new lighting system.



Parameter	Value
P	67.0 W
Φ_{lamp}	7906 lm
Luminous efficiency	118.0 lm/W
CCT	4000 K

Figure 4.19: Luminaires used in Case E: direct and indirect luminaires, with dimmable LEDs, suspended on tie rods. There are two rows of three elements, for a total of six luminaires.



(a) Isolux map of desks in Case E: $E_m = 310$ lx, $U_0 = 0.75$.

(b) Dialux rendering of Case E with isolux curves and colours on main surfaces.

Figure 4.20: Simulation results by Dialux in Case E for a situation with all lights ON, except for back luminaires that are on 50%, considering natural lighting too. The figures show a correct distribution of illuminance on floor and walls and a well-balanced illuminance on desks that receive direct light from luminaires and indirect light by reflections.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	400	0.80	13.1	🟧
	370	0.80	–	🟩
	250	0.40	–	🟩
Blackboard	230	0.95	18.4	🟧
	300	0.80	–	🟩
	230	0.40	–	🟩
Useful surface	350	0.60	–	🟧

Table 4.9: Dialux previsional evaluation for visual comfort in Case E for a light scene with all lights ON. This is the worse situation and the results are good. So in a normal situation, also with a low contribution of natural light too, luminaires can be switched at the 50% or more of their luminous flux.

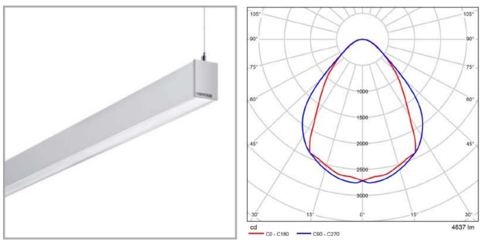
Measure	Value	U_0	Verified
M	0.40	–	🟩
E_0 [lx]	420	0.80	🟩
E_z [lx]	180	0.90	🟩

Table 4.10: Dialux previsional evaluation for desks lighting modelling in Case E. The results show a good distribution between direct and indirect light and light that reaches the students is good to evaluate the visibility of objects and the other people inside the room.

Case F

Inside this auditorium the acoustic component was solved with a high-performance surface treatment of the back walls. In addition, the current lighting system integrates quite well with the architectural part of the room and at the level of illumination and UGR on the desks it works quite well, despite not reaching the value of 500 lux. It was therefore decided to maintain the current positions and to replace the luminaires with others with direct distribution, using led lamps.

Figure 4.21: Case F rendering by Dialux.



Parameter	Value
P	53.0 W
Φ_{lamp}	4837 lm
Luminous efficiency	91.3 lm/W
CCT	4000 K

Figure 4.22: Lamps in Case F.

In a situation in which all the lights are ON and without natural light, the following parameters are reached (Tab. 4.11) and the illuminance of the visual tasks of the sessions are verified, both on the ground floor and on the mezzanine. The global average illuminance is also raised at the useful surface level.

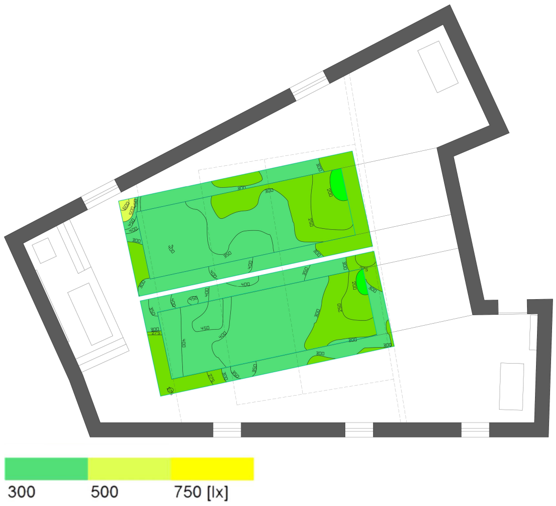
Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	590	0.55	25	🟧
	590	0.70	–	🟩
	310	0.01	–	🟧
Mezzanine	700	0.40	26	🟧
	320	0.02	–	🟧
	340	0.00	–	🟧
Blackboard	220	0.85	> 30	🟥
	200	0.75	–	🟧
	350	0.01	–	🟧
Useful surface	450	0.01	–	🟩

Table 4.11: Dialux previsional evaluation for visual comfort in a light scene where all luminaires are ON and without natural lighting: illuminance on mezzanine desks is too high but using dimmerable lights it can be reduced depending on the lighting situation of the moment.

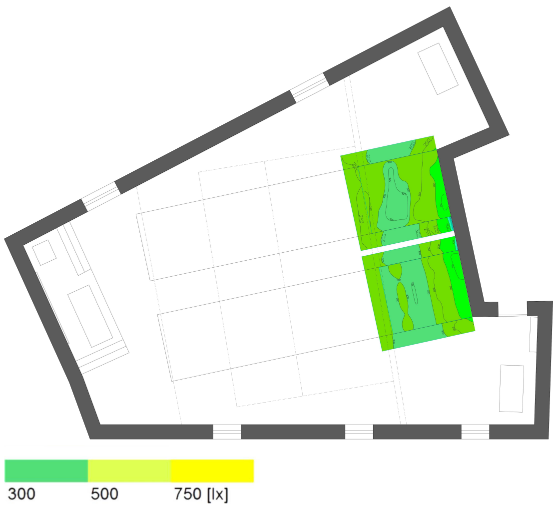
Figure 4.23: Special shape lamp for Case F frontal area.

Trying to break the rigor of the proposed lighting with these linear rows, the use of a luminaire with special shapes could increase the visibility of the frontal area, trying to make the environment less flat and boring (Fig. 4.23).

In this way the speaker area will be elevated and through dimmable LEDs it will be possible to raise or lower the luminous flux according to whether you want to give more or less importance to the frontal area.



(a) Isolux map of front desks: E_m = 350 lx, U_0 = 0.60.



(b) Isolux map of back desks: E_m = 340 lx, U_0 = 0.85.

Figure 4.24: Simulation results by Dialux of the desks visual task in a typical situation in which natural light is present and lights on desks are reduced (50% ON) to improve the frontal area of the blackboard.

Since the Case F is located on the second floor, natural light is usually present even if it does not reach the values required by UNI 10840 [4]. Furthermore, in a typical seminar light scene, the lighting on the desks can usually be decreased in order to emphasize the frontal area of the speaker.

Figure 4.25: Render by Dialux of Case F mezzanine in seminar light scene.

For a typical light scene for seminars, the mezzanine area is however well lit, with an average illuminance value (E_m) of about 300 lux. However, glare exceeds the values allowed by the standard [3].
As can be seen from Fig. 4.25, the same surface mounted lighting fixtures, led, with direct distribution have been used.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Mezzanine	360	0.45	24	■
	170	0.02	–	■
	240	0.00	–	■

Table 4.12: Dialux previsional evaluation for visual comfort in mezzanine, in a typical light scene for seminar, where light are 50% ON.

In general, for this type of scene, the lighting is well distributed and the modeling parameters meet the standard requirements.

Measure	Value	U_0	Verified
M	0.48	–	■
E_0 [lx]	449	0.85	■
E_z [lx]	217	0.94	■

Table 4.13: Dialux previsional evaluation for desks lighting modelling, in a seminar lighting scene.

Case G

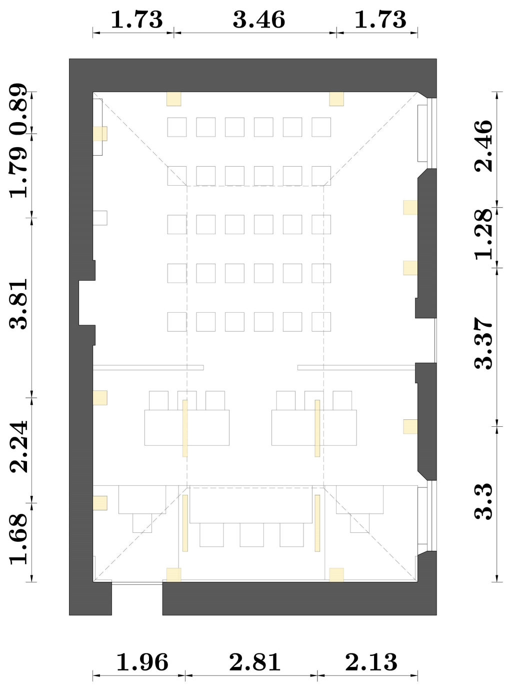


Figure 4.26: Project plan of the Case G Court–model.

For this premise, the client has planned a project of excellence, with the creation of a Court of law simulator, providing for a public area and a legal area, separated by a balustrade and providing a boiserie behind the legal area. The acoustic component involves the installation of a wall acoustic panel behind the public area.

For this type of scene, two main surfaces were considered, one for the legal area trying to guarantee 500 lux, and one for the public, trying to reach 300 lux for a simple visual performance (Fig. 4.27).

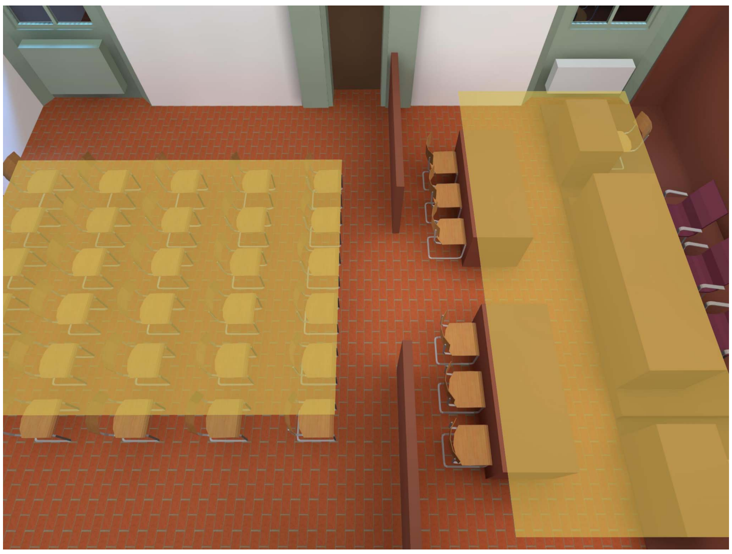


Figure 4.27: Surfaces considered for the Case G Court–model.

The stuccos surrounding the perimeter of the room were exploited, at a height of 4.35 m, to hide LED strips capable of providing diffused lighting, exploiting the reflection of the vault (Fig. 4.30). To raise the illumination on the legal area, direct lighting fixtures have been inserted, placed parallel to the visual ray, in order to guarantee adequate lux without exceeding glare (Fig. 4.31). Furthermore, in order to avoid having an area that is too dark on the public and to create a more dynamic, less flat environment, small ceiling lights with indirect lighting have been provided (Fig. 4.32).

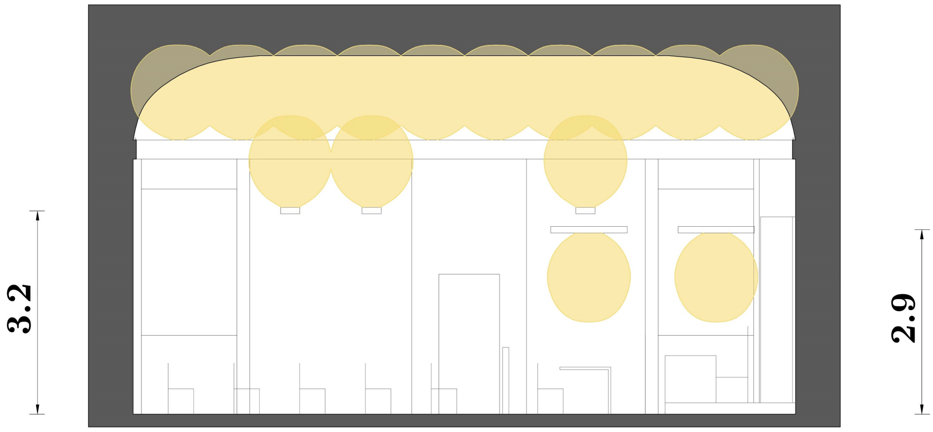
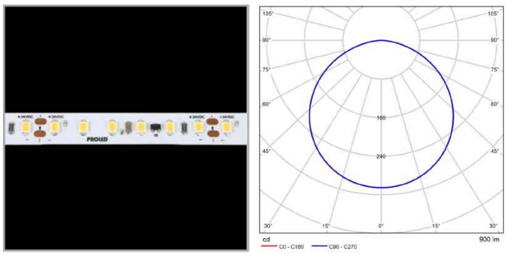


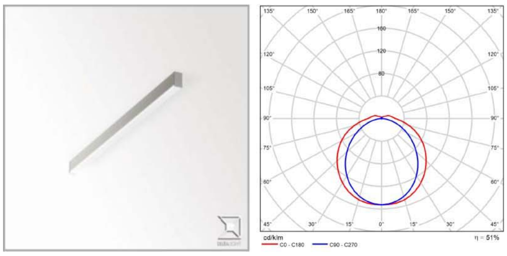
Figure 4.28: Section with luminaires distribution of the Case G Court–model.

Figure 4.29: Case G: Court of law simulator, rendering by Dialux.



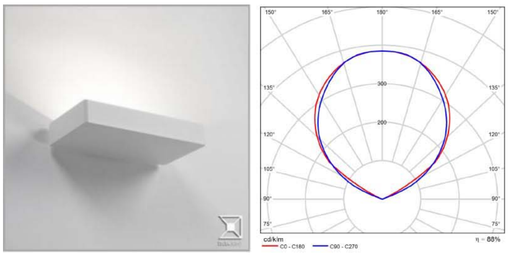
Parameter	Value
P	9.6 W
Φ_{lamp}	900 lm
Luminous efficiency	93.8 lm/W
CCT	4000 K

Figure 4.30: LED strips used in Case G Court–model.



Parameter	Value
P	56.0 W
$\Phi_{lightbulb}$	4450 lm
Φ_{lamp}	2253 lm
η	50.63 %
Luminous efficiency	40.2 lm/W
CCT	4000 K

Figure 4.31: Suspended luminaires used in Case G Court–model.



Parameter	Value
P	33.0 W
$\Phi_{lightbulb}$	3337 lm
Φ_{lamp}	2942 lm
η	88.17 %
Luminous efficiency	89.2 lm/W
CCT	3000 K

Figure 4.32: Wall-mounted luminaires used in Case G Court–model.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Front area	460	0.80	19	
Seats	330	0.85	18	

Table 4.14: Dialux previsional evaluation for visual comfort in Case G Court–model.

In general, for this type of scene, the lighting is well distributed and the modeling parameters meet the standard requirements. This means that lighting is well distributed between direct and indirect light and that people inside have a good sensation. The visibility is improved and this allows good communication and the recognition of the surround space.

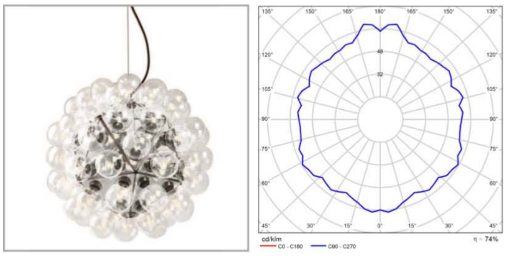
Measure	Value	U_0	Verified
M	0.40	–	■
E_0 [lx]	400	0.90	■
E_z [lx]	180	0.90	■

Table 4.15: Case G: Dialux previsional evaluation for lighting modelling.

Figure 4.33: Court of law simulator, rendering by Dialux: the isolux maps on the surfaces show a correct distribution of illuminance

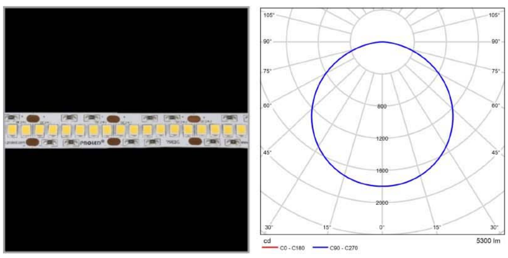
Case H

Since the acoustic intervention consists of positioning a carpet in order to increase its absorbent potential, in addition to replacing the current seats with more padded elements, the lighting technology can be developed without restrictions by the acoustic component. Being a noble hall with valuable surfaces, it was preferred to intervene as little as possible, taking advantage of the current positions of the luminaires and trying to give greater prominence to the architecture and decorations. The surfaces considered are the two seating blocks, the main desk and the surfaces of the paintings. It is advisable that these ones, since they are sensitive material, are exposed to no more than 200 lux, or in any case not more than 600000 lux·h/year.
Being a prestigious hall, two main lighting scenes were considered, one for seminars or graduation announcements and the other for any visits to the historic building. At the lamp level, the Taraxacum bulbs are replaced with other LED bulbs (Fig. 4.34); however, the mere presence of these luminaires, considering the worst case without natural lighting, does not satisfy the standard requirements, providing an E_m of just 200 lux on the visual task of the seats. It was decided to take advantage of the current positions by placing LED strips at the beginning of the vault, hidden by the stuccos, in order to create diffused lighting (Fig. 4.35) that alone can guarantee adequate values of E_m and UGR, for all the surfaces considered in the calculation.



Parameter	Value
P	420.0 W
$\Phi_{lightbulb}$	48360 lm
Φ_{lamp}	35734 lm
η	73.89 %
Luminous efficiency	85.1 lm/W
CCT	3991 K

Figure 4.34: Taraxacum with LED bulbs used in Case H.



Parameter	Value
P	57.6 W
Φ_{lamp}	5300 lm
Luminous efficiency	92.0 lm/W
CCT	4000 K

Figure 4.35: LED strips used in Case H.

For a lighting scene planned for seminars or graduation sessions, the use of indirect lighting alone is foreseen as it itself provides adequate lighting parameters and UGR. Auditorium requirements are not met, but in any case 300 lux is good for good lighting of visual tasks of normal performance. In this case, therefore, the illumination on the seating surface reaches 300 lux with very low glare, as well as on the main desk and on the lectern for the speaker (Fig. 4.36).

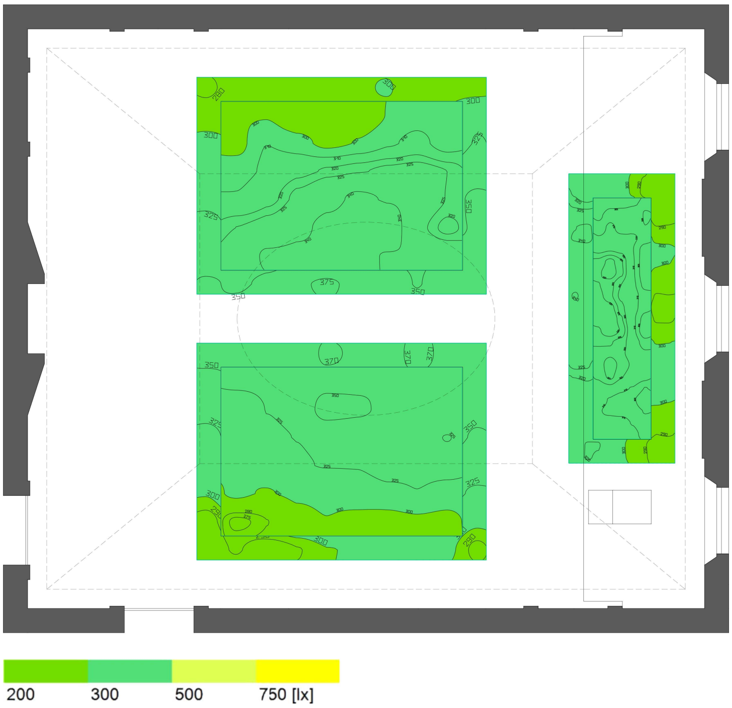


Figure 4.36: Isolux maps on seats surfaces and main desk surface in a light scene for seminars or graduation sessions. On desks $E_m = 330$ lx, $U_0 = 0.85$ and on teacher desk $E_m = 320$ lx, $U_0 = 0.95$.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Seats and main desk	320	0.90	< 10	■
	330	0.85	–	■
	250	0.70	–	■

Table 4.16: Dialux previsional evaluation for visual comfort in Case H in a light scene for seminars or graduation sessions: LED strips at 100% of luminous flux.

As can be seen in the Fig. 4.38, the illuminance on the paintings exceeds 200 lux (E_m = 280 lux). However, considering that the room is not used every day all day and if we consider an average use time of the daytime auditorium of 1401h and nighttime of 91h, in total in a year the paintings receive 420000 lux·h/year, therefore it is believed the solution as acceptable.

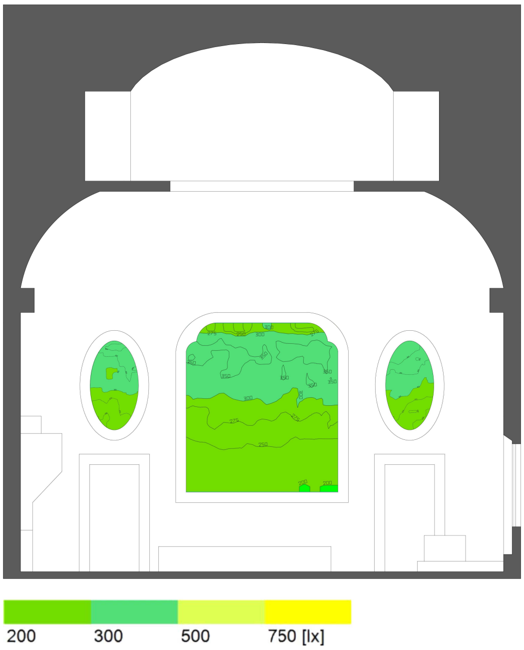
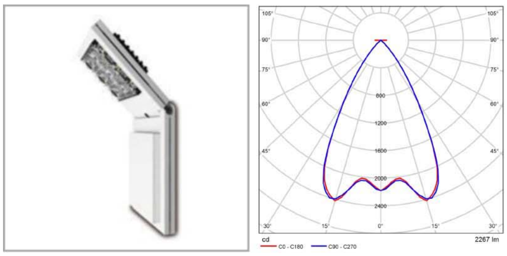


Figure 4.37: Section of Case H with isolux maps on paintings: E_m = 280 lx.

Figure 4.38: Isolux maps on painting and main surfaces in a light scene for seminars or graduation sessions: LED strips at 100% of luminous flux.

For a light scene designed for visits to the historic building, small rotatable wall applications have been provided, positioned at strategic points in order to raise the architecture and decorations of Case H (Fig. 4.39); also Taraxacum can be used in this scene. To have a better environment where people can comfortably visit the hall, LED strips can be used with 20% of their luminous flux.



Parameter	Value
P	21.0 W
Φ_{lamp}	2265 lm
Luminous efficiency	107.9 lm/W
CCT	4000 K

Figure 4.39: Small appliques used in Case H as light points to create dynamism and contrasts and elevate architecture and decorations. The luminaires are LEDs with the possibility of rotation in order to direct the flow according to user preferences.

Figure 4.40: Render by Dialux of Case H during visits to the historic building.

Case I

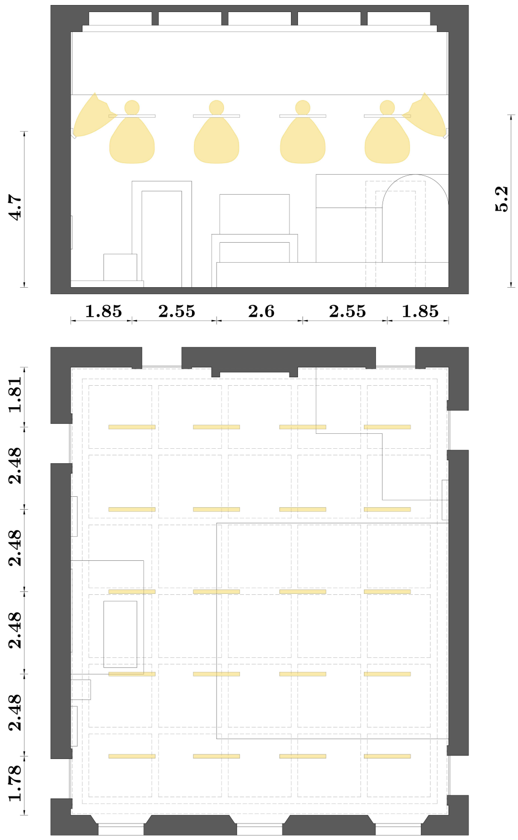
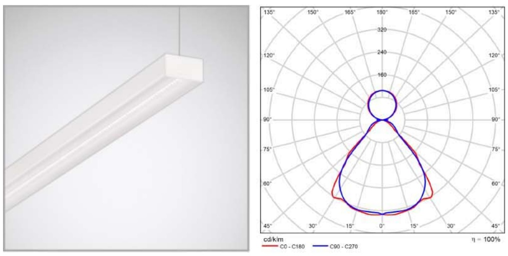


Figure 4.41: Plan and section of Case I with the lighting system and its luminous flux distribution.

Like the Case H, Case I also features prestigious architectural surfaces. The coffered ceiling is in fact painted and it is to be considered as a sensitive material, for which 200 lux of illuminance must not be exceeded. Overall, the room is very difficult to illuminate correctly in function of an auditorium and therefore it is difficult to reach 500 lux minimum on the visual task. In addition, Case I is subject to architectural, cultural and Superintendence constraints, therefore such that a lot of caution is required in the interventions. Case I turns out to be the most critical place in terms of lighting technology since if it were possible to reach the minimum illuminance it would exceed the glare, and vice versa. Various configurations were screened, initially with wall-mounted luminaires with very high luminous flux with diffused distribution which, despite everything, were unable to meet the standard requirements. Compatibly with the conservation constraints of the architectural heritage, the configuration illustrated below is proposed, trying to respect the constraints by making the room more functional. However, the minimum requirements are not achieved but it is still a more than satisfactory solution because it is better than the current state and closer to compliance with the standards. As in Case H, two configurations have been provided, one for lessons and the other for visits to the historic building.

In the configuration for lessons (Fig. 4.45), a suspended system was installed, suspended on tie rods, with dimmable devices, of moderate size so as not to obstruct the vision of the coffered ceiling in an excessive way. The luminaires, equipped with anti-glare blades, were positioned parallel to the visual range of the students, in order to reduce the glare index. These suspended luminaires have a mainly direct distribution, with a small indirect component so as to guarantee a correct distribution of illumination, in order not to have the surface of the ceiling in the dark and therefore guarantee uniformity of illuminance.

Figure 4.42: Render by Dialux of Case I in a light scene for lessons.



Parameter	Value
P	44.0 W
$\Phi_{lightbulb}$	6300 lm
Φ_{lamp}	6300 lm
η	100.00 %
Luminous efficiency	143.2 lm/W
CCT	4000 K

Figure 4.43: Suspended luminaires with anti glare blades used in Case I in a typical light scene for lessons.

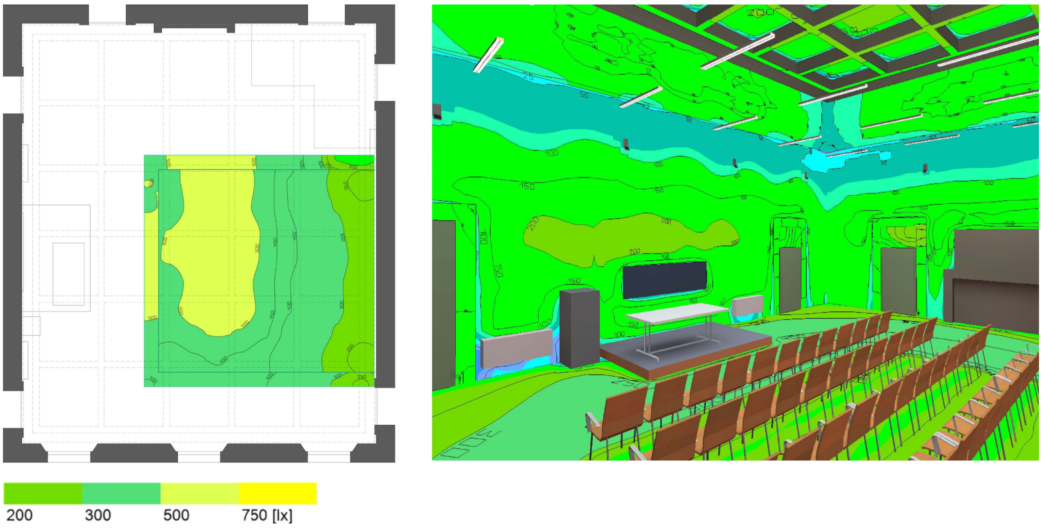


Figure 4.44: Isolux maps by Dialux of Case I in a light scene for lessons: on desks $E_m = 420$ lx, $U_0 = 0.60$.

Task	E_m [lx]	U_0	UGR_{max}	Verified
Desks	420	0.60	< 10	■
	420	0.40	–	■
	275	0.01	–	■
Useful surface	370	0.20	–	■

Table 4.17: Dialux previsional evaluation for visual comfort in a lessons scene.

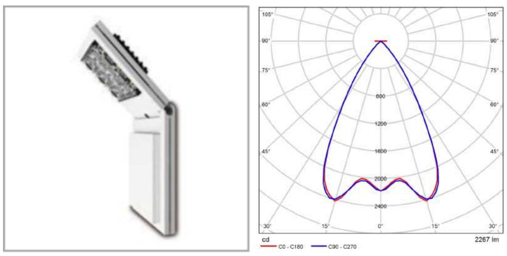
As the results in Tab. 4.17 and Fig. 4.44 show, requirements are not reached but the situation has clearly improved. The ceiling has$E_m = 140$ lx, less than the recommended value and distribution of illumination between the floor, walls and ceiling is correct, in fact modelling is verified (Tab. 4.18).

Measure	Value	U_0	Verified
M	0.35	–	■
E_0 [lx]	475	0.60	■
E_z [lx]	155	0.70	■

Table 4.18: Case I: Dialux previsional evaluation for lighting modelling.

For a light scene based on visits to the historic building, the same appliques used in Case H were chosen (Fig. 4.46), positioned on the wall around the perimeter of the room, with direct lighting towards the coffered ceiling, capable of providing an average illumination of 90 lux. This lighting system enhances the shape of the coffered by creating contrasts of shadows in order to enhance the shapes, without being flat (Fig. 4.45).

Figure 4.45: Render by Dialux of Case I during visits to the historic building.



Parameter	Value
P	21.0 W
Φ_{lamp}	2265 lm
Luminous efficiency	107.9 lm/W
CCT	4000 K

Figure 4.46: Appliques used in Case I for visits, the same used also in Case H.

Chapter 5

Discussion

Some considerations deserve to be made on the results previously exposed. In all the classrooms there has been a clear improvement in visual comfort in terms of lighting, uniformity and glare (Tab. 4.1, 4.3, 4.5, 4.7, 4.9, 4.11, 4.14, 4.16, 4.17). Also the parameters of punctual comfort were satisfied with regards to the visibility of the objects and the surrounding space and the correct balance between direct and indirect light (Tab. 4.2, 4.4, 4.6, 4.8, 4.10, 4.13, 4.18). As regards to the classic lighting parameters, as in the Table extrapolated from the EN 12464-1 (Tab. 2.5), the current state of the classrooms has been improved by approaching the minimum regulatory values. The complete fulfillment of the requirements has not always been achieved, but the situation has clearly improved compared to the previous one. In terms of lighting of the seats and desks, a value of 400 – 450 lux can be considered verified when the difference compared to the 500 lux standard is not significant. An illuminance greater than 300, on the other hand, does not satisfy the standard but is still a good value for visual tasks that need attention. As the table below shows (Tab. 5.1), the illuminances of the desks have improved at least 80% in all rooms, even reaching much greater improvements than 100% for those premises where the starting base was really poor, as in the Sala Feste (case L), a very dark room, with dark surfaces and currently lit with sodium vapor lamps emitting green frequencies.
In the smaller classrooms (cases A – E) in general, an illuminance of at most 300 lux is achieved on the blackboard level (Tab. 4.1, 4.3, 4.5, 4.7, 4.9), which can be improved since the minimum requirement is 500 lux (Tab. 2.5 from EN 12464-1). The projects were developed trying to obtain the minimum requirements mainly for the students desks, so that they saw their visual task adequately and had a good conception of the surrounding space. For the blackboard, a minimum of 300 lux was taken as a reference, without exceeding the glare.

With regard to greatest interest spaces, in Case F (Aula Magna) the situation can be further improved: in a light scene with only 100% artificial lighting, the glare values are still very high and, while the ground floor has a good illuminance with good uniformity, on the mezzanine the values are still very high and uniform (Tab. 4.12). Even the two noble halls perfomancre can be enhanced; the solution shown tries to approach the standard requirements while respecting the architectural and surfaces constraints, so it can be considered acceptable (Fig. 4.37 and Fig. 4.45). In the Sala Feste (case L) it would be better to have only wall-mounted luminaires in order to leave a complete view of the coffered ceiling; however, this types of configuration did not lead to satisfactory functional results, therefore a solution was studied to combine the practical aspect with the aesthetic one.

	A	B	C	D	E	F	G	H	L
E_m (*ante*) [lx]	270	220	210	280	160	280	130	120	50
E_m (*post*) [lx]	500	430	450	450	400	450	400	320	420
[%]	85	95	114	61	150	61	208	167	740

Table 5.1: Percentage improvement of illumination of the visual task of the desks (for the case F and G the useful surface was considered).

Regarding luminaries and design choices, in cases A to F the decision was to maintain the current positions of the lighting fixtures as much as possible, at least where their positioning was correct. In Case B (Fig. 4.6) the direction of the luminaires was correct (luminaires placed parallel to the visual ray with perpendicular anti-glare blades, with lighting towards the ceiling). The same position and directionality of light was maintained, but providing indirect lighting in the room. The acoustic baffles color was chosen in consultation with the lighting component to guarantee the same reflection coefficient of walls and ceiling in order to contribute to the distribution of light in the premise.
The same choice in color was also made in Case A (Fig. 4.2), in which instead the intervention involves a repositioning of the luminaires, always using direct and indirect light. In case C and D the current distribution was maintained (Fig. 4.10 and Fig. 4.14) while in Case E the same expedient was followed as in Case A, with the repositioning of the luminaires in a direction parallel to the visual beam (Fig. 4.18).
Concerning Case F, the replacement of the current luminaires with LEDs has been established as the current distribution integrated quite well with

the architecture of the lecture room (Fig. 4.21). To try to break the rigor of the premise and to increase the appeal of the speaker area, the idea was to insert a luminaire with particular shapes (Fig. 4.23).
Differently from the other rooms, Case G presented an excellence design given the client need of a Court simulator. The distribution of LED strips hidden by the stuccos and the presence of small ceiling lights created a dynamic environment with light contrasts on the walls. The integration of suspended luminaires on the legal area was necessary not only to ensure correct lighting of visual tasks but also to give greater importance to this zone compared to the public one (Fig. 4.29).
Cases H and I are the most valuable scenarios of all investigated. The lighting design based on standards and good practice had to be combined with architecture, valuable surfaces and other cultural heritage constraints. In the first case there were paintings and stuccos, for which 200 lx are recommended, not exceeding 600000 lux·h/year. In this room there were also 4 Taraxacum chandeliers designed for Flos by Achille Castiglioni. The replacement of the LED luminaires and the insertion of wall lights allowed to guarantee a good lighting of the seats in case of seminars and to elevate the architecture showing its value and beauty in case of visitors (Fig. 4.40).
Case H, Salone delle Feste, was the most critical in terms of lighting design: it is a place of considerable historical value subjected to cultural, architectural and Superintendency constraints, used for seminars but poorly lit. Various distributions were screened in the way to interfer as little as possible with the aesthetics of the Salone but in the end it was decided to use moderate size suspended devices, trying to satisfy architectural and functional needs (Fig. 4.42).

5.1 Comparative analysis of consumption

As explained by Li, Lam and Wong [34], artificial lighting represents 20–30% of the total energy of a building; even more in environments such as schools where the light often remains on even in unused spaces. Therefore, the lighting system was designed not only to provide users with adequate visual comfort, but also to increase the energy efficiency of the entirety. In general, the lighting system at present is made up of fluorescent tube lamps, whose majority of energy consumed for their functioning is dissipated in the form of heat and whose useful life is limited, with also high maintenance costs. Therefore it was decided to intervene not only through the redesign of the dispositions, but also by implementing the so-called relamping with LED sources. In fact, the use of this technology has advantages in terms of low consumption and therefore economic savings, lamp life and low return on investment times. To compare the current situation with that of the project in energy terms, the LENI [9] index was calculated using the Dialux software and through a excel sheet (Tab. 5.2). The first follows what reported by the 2007 standard, which presented a less detailed approach to estimate the contribution of natural lighting in energy performance.

Case	$LENI_{sub}$ ante-operam		$LENI_{sub}$ post-operam	
	Calculation result	Previsional model	Calculation result	Previsional model
A	10.6	6 – 9.00	8.9	7 – 11.00
B	12.5	9 – 14.00	9.9	8 – 13.00
C	16.4	14.00	11.7	15.00
D	15.5	11 – 18.00	8.3	6 – 10.00
E	8.1	8.00	10.5	9 – 14.00
F	24.1	17 – 24.00	10.9	8 – 12.00
G	9.3	7 – 9.00	13.2	12 – 18.00
H	52.0	39 – 62.00	22.9	21 – 34.00
L	4.5	2 – 3.00	8.7	7 – 10.00

Table 5.2: Comparison between LENI index in current state and design state for each case evaluated with standard recommendations and with previsional model software. Used standard is EN 15193:2017 [9] while previsional model follows EN 15193:2007 instructions.

As expected, in general the value of the LENI has decreased compared to the previous situation: the LED installation has lead to a decrease in energy consumption for lighting and this is also reflected in the decrease in this index. In case E the index goes from a value of 8 to a value of about 10: from three luminaires with two 35 W lamps it has gone to six LED lamps with 67 W. However, this makes perfect sense thinking about that in this way higher lighting requirements are satisfied, going from an average illuminance of 160 lux to a value of almost 500 lux. Even in case G and in case L a higher LENI value is obtained: in the first case it is a consequence of the fact that for a Court simulator the requirements to be met are higher, in the second case it is increased considerably the visual comfort while respecting the architectural and cultural constraints, in a premise where the initial lighting was really poor for comfort of users.

5.2 Evaluation of relamping times

After the installation of the new LED system, it is of fundamental importance to guarantee its maintenance over time, in particular its performance. Proper maintenance plays a key role in the management of the system: the goal is that the designed lighting system maintains the requirements established in the design phase, guaranteeing, during its life, the correct lighting necessary to carry out the visual tasks and to have a correct visual comfort. The decay of the luminous flux of the luminaire depends on the progressive deterioration of the system, in relation to the type of luminaire and the conditions of the environment (for example, the soiling of walls involves a reduction in the reflection of light). To remedy this problem, a maintenance factor, MF, equal to 0.80 was defined in the design phase as recommended by the Dialux software. The transition from fluorescent to LED technology also leads to an improvement in terms of maintenance as the useful life is different and this also reflects on the maintenance program to be adopted. According to the technical report 97-2015 of the CIE [5], the trend of the luminous flux as a function of the hours of use for linear fluorescent lamps shows a decrease due to losses due to the soiling of the room (curve A), to losses attributable to the lamp itself (curve B) and the luminaire (curve C). It is possible to establish an optimal interval for lamp replacement which essentially depends on the lamp life factor (LSF) and the luminous flux maintenance factor of the lamp (LLMF). The first represents the probability that the lamps continue to operate after a certain period of time and provides indications on the number of lamps; for these evaluations, the manufacturer provides the hours of operation of the lamps in correspondence with 50% (LSF = 0.50) of the lamps that survived following a test [5]. The second instead is defined as the ratio between the luminous flux emitted by the lamp in a given instant and the luminous flux initially emitted (for fluorescent lamps it can be considered in a range of 0.75 – 0.90). The optimal period for replacing fluorescent lamps is equal to 80% of the useful life of the lamp, since for higher values there is a rapid decrease in performance in terms of luminous flux emitted [1].
In general, for example, taking into consideration the average life of the lamps shown in Tab.1.2, for a fluorescent lamp with a characteristic duration of about 12000 hours (at LSF equal to 0.50), the relamping duration is 9600 hours, assessed as 80% of the useful life, as specified above. Considering the typical annual operating hours for schools (burning hours = 1900) provided by CIE 97-2005 [5], the interval in which to make the replacement can be evaluated as:

$$\text{relamping interval} = \frac{\text{relamping duration}}{\text{burning hours}} = \frac{9600}{1900} = 5 \text{ years} \tag{5.1}$$

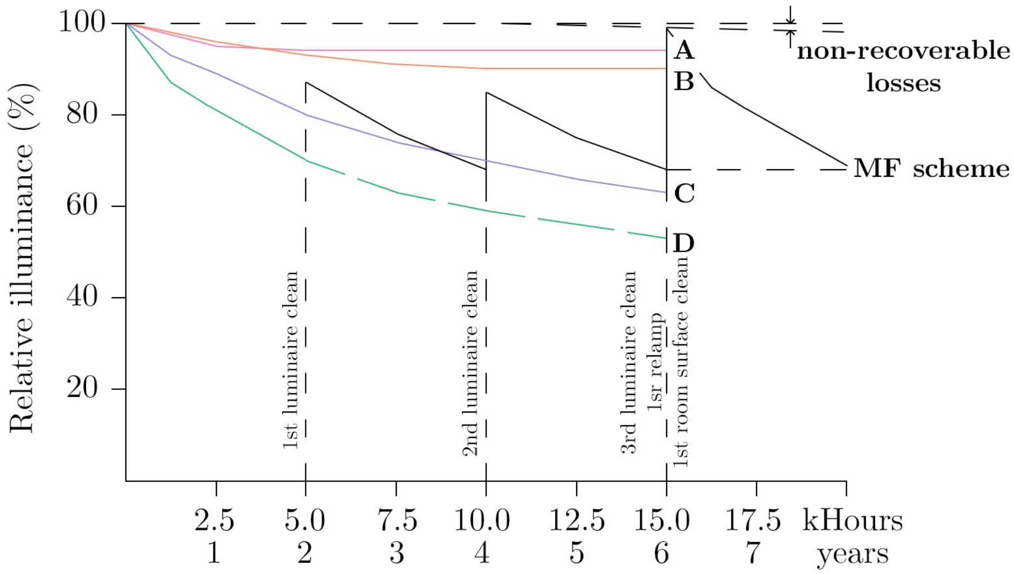


Figure 5.1: Variation of illuminance through life (linear fluorescent lamp in industrial reflector luminaire operated with spot lamp replacement programme). Curve A is the room surface maintenance curve; Curve B is the lamp lumen maintenance curve; Curve C is the luminaire maintenance curve; Curve D represent an un-maintained system output [5].

The degradation of the LED characteristics, on the other hand, occur mainly due to the operating temperature of the lamp. To take into account the decay of the luminous flux, the useful life of LED is defined according to EN 62717 [11] through the wording $L_x B_y$. L represents the percentage of decrease in luminous flux compared to useful operating hours while B is the percentage of LED which at the end of the hours does not maintain the declared characteristics: if the value is not defined, it is to be understood as 50% [11]. For example, if the LED in question is characterized by the abbreviation $L_{70}B_{20}$, this indicates that, upon reaching its useful life, 80% (B_{20}) of the LED has a residual flow equal to or greater than 70% of the initial flow (L_{70}).
For the evaluation of the time after which to replace the LED luminaires, the decrease in luminous flux declared by the manufacturer was considered. In the simulations carried out using the Dialux software, a MF (Maintenance factor) of 0.80 was chosen: this means that it is considered necessary, in order to guarantee the lighting of the project, to change the luminaires when they emit 80% of the initial luminous flux. Table 5.3 shows the estimate of the effective duration of each type of device and the relamping interval, considering for cases A – E and for cases F – L yearly burning hours for classrooms and auditorium respectively. It is possible to observe how the relamping time re-

	Luminarie model	L_xB_y	D_c [h]	D_e [h]	h_{burn} [h]	Relamp [years]
A	Sl720PL microprisma	L80B10	50k	40k	2750	15
B	Linux DALI ASL1778	L85B10	50k	40k	2750	15
C	Trimpak	L80B50	50k	40k	2750	15
	Book Sink IP40	L80B10	50k	40k	2750	15
D	SL720PL microprisma	L80B10	50k	40k	2750	15
E	SL720PL microprisma	L80B10	50k	40k	2750	15
F	SL764PL M	L80B10	50k	40k	1500	27
G	FlexStrip 600CC Mono20m–NW	L80B10	50k	40k	1500	27
	z–microline 30+P1154	L70B50	50k	30k	1500	20
	GALA XL HP930 DIM1	L80B10	50k	40k	1500	27
H	Book Sink IP40	L80B10	50k	40k	1500	27
	FlexStrip 1200HE Mono–NW	L80B10	50k	40k	1500	27
L	Flow H2–L MRW 6400-840 ET01	L80B10	50k	40k	1500	27
	Book Sink IP40	L80B10	50k	40k	1500	27

Table 5.3: Relamping interval for the LEDs according to the yearly hours of use. The characteristic duration (D_c) has been decreased (D_e) as a precaution based on the simplifying hypothesis that the decrease in time of luminous flux emitted by the fixtures is almost linear [1].

quired changes strongly between the LED and the fluorescent scenarios: the current state devices replacement intervals are much longer compared to the ante-operam state, despite the precautionary estimates of effective duration considered.

5.3 Subjective evaluation of visual comfort

The analysis of global comfort becomes of fundamental importance in environments dedicated to education; it is a multidisciplinary theme that requires investigation from various fields from engineering to psychology. A

combination of measures in situ and questionnaires dedicated to specific users provides a better and more complete overview about the general well-being of the occupants. Regulatory requirements may be verified but user comfort may be unsatisfactory. Various studies have proposed this method of investigation in order to find a correlation between objective measures and subjective answers [38][13][16]. These studies assessed the importance of environmental conditions for comfort by asking users to fill in a questionnaire indicating their degree of satisfaction regarding various aspects, from thermal, to acoustic and lighting comfort, in general on the IEQ. The responses were used to estimate the contribution of satisfaction of the various parameters to the overall satisfaction of the environment.
In the work presented by Ricciardi [16] a questionnaire on lighting was proposed in order to obtain subjective information from the point of view of users relating to artificial and natural lighting. The questionnaire was divided into three parts: the first on personal data and the characteristics of the lecture room, the second on the perception of artificial lighting and the third on natural light. More specific questions about annoying glare and the possibility of too limited or too low light contrasts were also included. In each question an answer was required on a scale from 1 to 10. Based on the answers, a critical analysis was carried out comparing the results with the experimental ones. In this way, each response was correlated with each measured value in order to evaluate which subjective parameters are more related to the experimental measurements.
New indexes have been introduced within the questionnaire [16]:

- ALQ: quality index of artificial lighting
- SLA: index of artificial lighting sources
- ALG: annoying glares index of artificial lighting
- NLQ: quality index of natural lighting
- NLR: Natural Lighting Reflections Index.

It is important to observe that for indexes ALQ, ALS and NLQ, higher values corresponded to good comfort conditions. For ALG and NLR higher values corresponded instead to bad conditions, due to annoying glares and external reflections, so it was necessary to evaluate the complementary votes (10 – ALG) and (10 – NLR), in order to comment the results in terms of visual comfort [16]. After receiving the results, it is important to carry out a critical analysis of the responses in relation to the parameters measured following the intervention in order to identify overstatements or underestimates in the user's perception regarding problems and improvements.

Conclusions

Correct lighting design is essential for better learning in school settings. Adequate illumination of visual tasks together with its uniformity in the environment allows to meet the needs of visual performances in order to achieve a certain level of attention and productivity. Therefore a lighting intervention becomes fundamental in those spaces where the minimum conditions are not respected, as in the nine case studies presented in this thesis. The design in Palazzo malvezzi-Campeggi should care about architectural and cultural constraints so that technical requirements can meet aesthetic istances.
The simulations conducted with Dialux certified lighting software were supported by inspections and photoreliefs. It was thus possible to ascertain the insufficient performance of the lecture halls and identify their critical issues. The results show that natural lighting is practically null in almost all the cases considered. Correct lighting engineering redesign therefore becomes essential in spaces where daylight is poor and the lighting system is inadequate and incorrectly installed. Using the same method, it was possible to identify the correct design proposals that raise the main lighting parameters within acceptable values. For some environments of particular value used for ceremonial or representative purposes, a further in-depth study provides different light scenarios according to the specific use in relation to the different occasions. Furthermore, the theatricality and the rendering of the artistic surfaces can be verified in a more accurate way during the installation phase. Both ante-operam and post-operam, the parameters were expressed in relation to the standard requirements as reported by EN 12464-1.
The project proposals led to an improvement in energy efficiency represented by the decrease in the LENI index, which specifies the energy consumption of a lighting system, expressed in kWh per square meter per year, according to standard EN 15193. Given a marked improvement in visual comfort, a moderate increase in energy performance is expected. The same cannot be said for some lecture halls where comfort has been raised from a particularly bad condition and there has been an increase in consumption which, however, is acceptable because a substantial improvement compared to the previous

condition is provided. The new LED system allows to reduce consumption, improving performance in terms of duration and maintenance. This technology makes possible to have a higher relamping interval compared to a typical educational scenario in which linear fluorescent lamps are mainly used.
Following the installation of the proposed system, measures during the testing phase will then be necessary to verify its effectiveness and highlight any unexpected critical issues. In order to verify the effective performance of the new proposed solutions, measurements could be made after a significant period of time to check the stability of the system even after normal university use. In this way it could be better understood how performance decays over time and how devices wear out, evaluating if maintenance is suitable or if it must be increased.
Since the perceptual component is important for visual comfort, it could also be useful to propose questionnaires to students in order to obtain feedbacks on lighting conditions after the new intervention. The questionnaire could be divided in such a way as to identify the perception of the individual user about artificial lighting, with a section for natural light, together with questions on glare and light contrasts. In this way, the quantitative data of the previsional evaluation and in situ measurements would be related to the users' subjective qualitative data, giving an overview of the lighting comfort.

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