Culture and Methods of Lighting Design

Maurizio Rossi

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Preface

Lighting Design is a technical and creative activity influenced by cultural, perceptual, technological, communicative, methodological, and economic aspects. It is multidisciplinary. The need to manage a medium as intangible as light presents technological and methodological difficulties in developing projects. Today's lighting project requires operators capable of effectively connecting the perceptive, technical, economic, and socio-cultural dimensions and of starting from here to propose new design syntheses. In this context, the most relevant changes are to be found in methodological and technological innovations, represented by international standards, new light sources, and innovative tools that information technology (IT) and the Internet have made available to support the process of lighting design. Until the advent of LEDs, the way of designing lighting evolved slowly over a century, hand in hand with the development of technological innovation typical of the electromechanical industry. In recent years, however, companies in the lighting industry have been busy metabolizing the new lighting technology represented by LEDs, which have almost replaced other artificial light sources. LEDs are photoelectronic components and lighting companies, accustomed for decades to working in the electromechanical sector, had to quickly acquire skills in the electronics sector and adapt to the rapid development of products in the electronics sector.

The first chapter introduces the culture of lighting design in the relationship between human beings, understood as users or designers, and lighting. The figure of the designer develops in the relationship between social tasks, technical skills, and the definition of the professional profile of the Lighting Designer. In the methodology of design, there are new drivers of innovation, which in less than fifteen years have led to a radical change in the working methods of the designer.

The second chapter focuses on the ways in which artificial electric lighting has changed the lives of humans over the past century. It also analyzes the leading areas of research and development in the field of lighting and the consequent areas of intervention of the lighting design work in a period, such as the current one, of strong innovation in tools and methods.

The past decade has seen the proliferation of new standards that define quantitative requirements and introduce qualitative lighting criteria. In the third chapter, attention is paid to methods resulting from the environmental sustainability issue, the aspects relating to energy savings, the end-of-life of lighting products, and the regulatory situation.

The fourth chapter examines human beings and their visual perception. Color and light are two aspects of the same visual sensation and must be considered in the context of our visual system's perceptual adaptation. The human visual system (HVS) is then placed in relation to the lighting project's process aspects and the potential and limitations of virtual project simulation to evaluate the qualitative and perceptual aspects of lighting.

This book was born from research at the Lab. Luce and teaching experiences, gained since 1997 at the Politecnico di Milano, in addition to experiences in the direction of the Master in Lighting Design & LED Technology and the Master in Color Design & Technology.

Maurizio Rossi

Short biography of the author

Full Professor of Design- tenured at the Design dept. of the Politecnico di Milano since 2019. Previously, from 2002 to 2010, assistant professor and, from 2010 to 2019, associate professor at the Politecnico di Milano. Scientific Manager of the Laboratorio Luce of the Politecnico di Milano since 2002. Since 1998 he has directed 25 research projects on light an color funded by public tenders or research contracts/conventions, 24 at the Politecnico di Milano. Member of the Faculty of the Ph.D. in Design of the Politecnico di Milano.

At Politecnico di Milano he teaches in the courses of Lighting Design and Design Methods. Since 2010 he has been the director of the Master in Lighting Design & LED Technology of the Politecnico di Milano. Since 2014 he has been the director of the Master in Color Design & Technology of the Politecnico di Milano. Director of 51 lifelong training courses organized firstly by the In.D.A.Co. Dept. and then by the Design dept. of the Politecnico di Milano. Director of 33 higher education courses of the Poli.Design consortium.

Vice-President of the AIC-International Colour Association 2022-2023. President-Elect of the AIC-International Colour Association 2024-2025. Since 2018 member of the Executive Committee of the AIC-International Colour Association. Since 2021 he has been a member of the Board of Directors of SID-Società Italiana Design. President of the GdC-Associazione Italiana Colore from 2012 to 2018. Since 2012 he has been a member of the Board of Directors of GdC-Associazione Italiana Colore.

He has published 166 scientific publications, including 6 books as author, 16 as editor, 18 essays in books, 15 articles in international journals, 7 articles in ANVUR class A journals, and 20 in ANVUR scientific journals, 55 papers in international conference proceedings as well as other publications. Since he is 2014 editor-in-chief of the Color Culture & Science Journal. He was chair of 10 international conferences in the English language. He was a speaker at 17 international conferences.

PhD in Computer Science at the Università degli Studi di Milano in 2004. Degree in SS.MM.FF.NN. at the Università degli Studi di Milano in 1989.

Chapter 1

Lighting Design: culture and profession

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Abstract

This chapter introduces the culture of lighting design in the relationship between human beings, understood as users or designers, and lighting. The relations between light and humans evolved over thousands of years from a cultural and scientific point of view. The figure of the designer develops in the relationship between social tasks, technical skills, and the definition of the professional profile of the Lighting Designer. In the methodology of lighting design, there are new drivers of innovation, which in less than fifteen years have led to a radical change in the lighting designer's job. Some of the most relevant drivers are IT tools for virtual design verification and smart lighting control. Apart from technology, the designer's choices can make any project unforgettable or sink its quality, invalidating the efforts of all other figures involved in the design process. This is true for general lighting and for the exhibition and show. In reality, this is a mix of color and lighting design, with varied and fascinating contents that must be known and valorized.

Keywords

Lighting design, light history, culture, science, entertainment

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1.1 Introduction to human beings and the sunlight Gods

Before talking about new methodologies and technologies, let us introduce the historical-cultural aspects of the relationship between human beings and light.

Light and vision, a natural phenomenon and a perceptual sense that characterize the existence of human beings. How many people in daily life grasp how much light permeates all of our activities? Although in modern civilization light has become an object of scientific study explained through various physical models, it is still as obvious as air, which does not raise questions in most of us. This introduces the topic of light in ancient cultures and how this light was related to the Sun. And even without a scientific culture, the Sun was reasonably considered the origin of life (Singh, 1993).

In the ancient Sumerian scriptures, the Mesopotamian Sun God Utu reappeared illuminating the sky and Earth after the Great Flood, and Ziusudra (Noah) then made an opening in the boat, through which Utu also lighted the interior, thus defeating the darkness. Utu was worshipped for more than 3000 years up to the end of the Mesopotamian culture, starting from around 3500 BC.

In Heliopolis, the ancient Egyptians worshipped Ra, the Sun God, with a hawk's head and human features, placing him at the center of their religious culture. For the Egyptians, other likenesses of the God included Atum and Kepri. In many situations Ra was represented as a hawk carrying the bright disk of the Sun above his head. Some cultures identified the Sun crossing the sky with the body of the Sun God, while others believed it to be his eye. In its double meaning of God, Atum-Ra was a creator deity with the gift of bestowing life: his tears were believed to have created the human race. In the New Kingdom, in Thebes, the Sun God bearer of light was identified with Ammon. He was also credited with the creation of intelligence and reasoning. In fact, it was believed that during circumcision, by injuring his phallus, Ammon lost drops of blood that would be transformed into the authority Hu, and the intelligence Sia, which represented the intuitive qualities of intelligence and the power of intellect.

In Buddhist mythology, Mārīcī is the God, sometimes represented as a Goddess riding a boar, representing the light and the Sun. Some of his earliest iconographies are in India and Tibet, where Marici is depicted driving a chariot pulled by seven horses, similar to the other Sun deity Surya. In Chinese mythology, the cosmic Goddess of heaven, Dǒumǔ, from the Tang dynasty of Chinese Buddhism was confused with the Goddess Mārīcī.

Figure 1.1 - Ra, the Sun God of the ancient Egyptians represented with a hawk's head surmounted by the Sun.

Figure 1.2 – A representation of the Nānahuātl God, from the Yoālli Ehēcatl pre-Columbian manuscript (around XV Century).

In the empire of the Incas, born from the conquest of many tribes bordering their own, religion assimilated many of the cultural traditions of the conquered peoples. One of these was Inti, the Sun God. The latter was considered the true creator of the Incas and it was Inti who, according to an ancient legend, had given Manco Capac, the first Inca emperor, the golden rod that would allow him to find the place where Cuczo, the ancient capital of the empire, would be built.

According to Aztec mythology, the Nānahuātl God sacrificed himself in fire in order to shine on Earth, thus becoming the fifth Sun God. They thought that the previous four Sun had been destroyed by the hurrincanes, the jaguars, the rain of fire and a great flood. In the legend of the serpent God Quetzalcōātl, Nānahuātl helps him to obtain the first seeds of agriculture in what will become the food of humanity, thus placing the Sun God at the basis of agriculture and nutrition.

Among the Celts, the Druids, men of culture and priests of the ancient people, have always claimed the paternity of Stonehenge in England. Still today, every year, at dawn on June 21, the place is a destination for many tourists and curious people, who go there to see the Sun rising at the alignment between the Hell Stone and the center of the monument. For this reason, scholars believe that the henge monument is a temple to the Sun God. Belenus is the Proto-Celtic god of light and healing, whose cult developed from the Italian peninsula to the British Isles. While Étaín is the Irish goddess, she is considered a solar deity. In the Celtic Baltic, Saulė is the most powerful solar goddess among the deities because she is responsible for heat, fertility, life, and health.

From the Neolithic, and perhaps even earlier, until the Roman age, the pagan communities of Europe drew symbols, built shrines and fashioned images corresponding to the daily and seasonal movement of the Sun, to its essential properties as a source of light and heat, to its many positive values for the life of human beings. Like Usil, the Etruscan solar deity is similar to the Greek God Helios and the Roman God Sol. The image of the Sun God in the Roman-Celtic Europe shows, at least in its most evolved forms, functions that, in previous periods, were only implied: the powers of the Sun govern the cosmos, protecting humans and animals, and it is always these powers that regulate the main human activities, the reproduction of the species, breeding and agriculture, death and rebirth in the afterlife.

The attitude of human beings in antiquity towards the Sun can perhaps be compared to that of the great Flemish painter Vincent Van Gogh, who, during the period of his life in Arles, was obsessed and fascinated by the light and color of the Sun. It is in fact in the sudden awareness of the Sun as a source of light that the great painter recognized the secret of life and expressed his art.

1.2 Light in the history of science

Light is life. Without sunlight, with its alternating sunrises and sunsets, there would be no life on earth. Light is also energy. All human activities are directly or indirectly affected by light radiation (Rossi, 2019). If, absurdly, the sun suddenly went out, all the most modern human technologies would not be able to sustain the survival of our species.

By limiting the analysis of light to the aspects of visibility alone, the scope of natural and artificial illumination nevertheless extends to all bases of human culture. Visual communication, the perception of colors and shapes, are possible only thanks to the information that light carries to our sensory organs responsible for vision: the eyes and the brain (Zeki, 1993).

The images we perceive are the result of the brain's cognitive perception of light reflected from the surfaces of objects to our eyes. When we see an object, it is because it reflects light from other surfaces or emits its own light. The same shapes can appear different depending on the type of light they receive (Gregory, 2015); in fact, illumination can vary in terms of color but also according to the set of directions from which it comes; in addition to the geometric shape of objects, we can also consider the shape/direction of light, but this is much more difficult to define and technically control than geometric shapes. If we consider a sculpture such as Michelangelo's Pietà, characterized by a marble surface with a homogeneous chromatic aspect, we can observe that the perception of such a valuable work of art is possible thanks to the presence of lights and shadows on its surface. Assuming to illuminate the work through an absolutely uniform illumination on all its surface, the absence of different levels of illumination and luminance perceived by the eyes of the observer would not make it possible to identify points of reference on the statue and therefore would make difficult also to perceive depth and shape.

For centuries, scientists have been trying to describe light using physical and mathematical models. Observing that light does not go around obstacles but propagates in a straight line, in the seventeenth century Isaac Newton assumed that the only possible explanation was the one already proposed by Pythagoreans almost 2000 years earlier. The light had to be composed of a beam of tiny particles launched from the light source at very high speed; these, hitting objects, made them appear illuminated. And this was the theory he proposed in his famous treatise on Optics, published at the beginning of eighteenth century (Newton, 1704).

At that time the laws of reflection and refraction of light were experimentally known and represented a good test to demonstrate the validity of the various theories on the nature of light. The law of refraction states that when a light ray crosses the separation surface between two media, in which light can propagate, then the incident ray, the transmitted ray and the normal lie in the same plane and the sine of the angle of refraction is proportional to the sine of the angle of incidence according to the difference in density of the two media. The law of reflection states that the incident ray, the reflected ray and the normal to a surface at the point of reflection lie in the same plane, and furthermore the angle of reflection is equal to the angle of incidence.

Using the laws of corpuscular mechanics, Newton was able to describe the phenomenon of light reflection. According to this model, light corpuscles behave like spheres thrown against a well-smoothed rigid surface. Indeed, it is possible to verify that if a sphere arrives on a rigid surface with a certain angle of incidence it bounces with an angle equal to the angle from which it comes. The different colors of light were explained by the different speed of the corpuscles hitting the eye: for example the fastest corpuscles would give the violet effect and the slowest corpuscles the red effect. Newton also tried to explain the phenomenon of refraction of light with the corpuscular model, but according to this model the speed of light had to be greater in the most refracting media. Newton himself affirmed that if some experiment had demonstrated the contrary, his corpuscular theory had to be abandoned; nevertheless, considering the importance that at that time Newton had as a scientist and as a politician, his theory dominated for the entire century following the publication of his work.

A contemporary of Newton, Christiaan Huygens, formulated the the wave theory of light, stating that this should be composed of a set of small vibrations and that the different colors of light should be attributed to different wavelengths (Huygens, 1690). This theory explained well both the phenomenon of reflection and refraction and also chromatic dispersion. However, it raised at least two questions: if light is a wave, why do shadows form? That is, why does it only propagate in a straight line? In fact, in the seventeenth century many laws of acoustics were already known, in particular that sound waves can propagate also with a spherical wavefront as it happens with the waves originated from a stone thrown into a pond. For Huygens the biggest problem was the fact that light also passed through vacuum and therefore he asked himself what was the medium through which the light wave propagated. To give an answer to this question, which was of primary importance for the wave theory, a dogma of the ancient

Greeks was revived, i.e. the existence of an invisible and intangible substance that permeates all creation: the ether. According to Huygens, light would be a wave propagating through this substance.
Which of the two assumptions was correct? The corpuscular theory seemed to interpret well the phenomenon of shadow formation while the undulatory theory was able to explain most optical phenomena in an elegant way. Only towards the middle of 1800 a French physicist (Fizeau, 1851), measuring the speed of light in water, verified that it decreased in denser media; therefore the corpuscular model for the description of refraction could not be considered valid. Fizeau was the first to measure the speed of light in air and water in 1849. Along with Focault, he was also the first to take a clear photograph of the surface of the sun. At the beginning of 1800 other experiments showed the prevalence of the wave theory on the corpuscular one. These experiments were the work of the English scientist Thomas Young and the French physicist Augustin Fresnel. Thomas Young, an English physicist, physician and Egyptologist was also involved in studies of the eye and the description of astigmatism; he also participated in the decipherment of the Rosetta Stone.

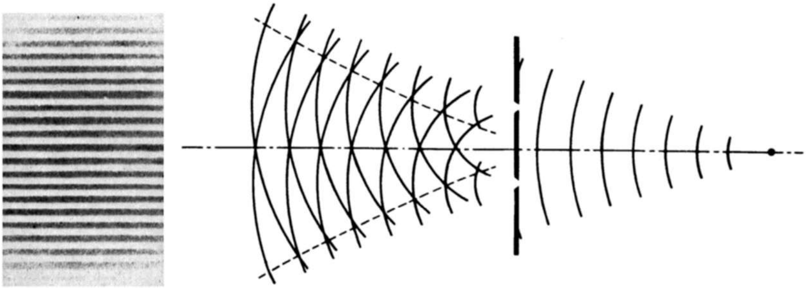

Figure 1.3 - Thomas Young's experiment that showed the phenomenon of diffraction and light interference.

In his experiment Young sent a beam of monochromatic light toward two small slits a short distance apart. The light coming out of the holes did not proceed in a straight line but widened to form two cones. The light collected on a screen formed a region where the two light beams were superimposed and not two individual illuminated areas, as it might be expected from corpuscular theory. In addition, in the region where the beams overlapped, the illumination did not appear more intense but very bright areas and areas of darkness were observed (Young, 1804). Through this experience Young observed certain phenomena that proved to be fundamental in understanding the nature of light. One phenomenon, i.e. the widening of light beams, is called light diffraction and is a direct consequence of Huygens' principle. A wave passing through the opening takes on a circular appearance, propagating in directions oblique to that of arrival. Therefore, one might think that light is a wave phenomenon like the waves of the sea. Not only that, this hypothesis is strengthened by the observation of the behavior of the encounter of two waves, where very high wave peaks and lower ones can be observed. It should then be noted that a slit opening much larger than the wavelength does not produce a significant effect. In his experiment, Young used very small slits but with larger slits only two bright spots appeared on the screen. The conclusion is that light is an undulatory phenomenon with very small wavelength. If light produces shadows with defined contours, it is because the objects around us are much larger than the wavelength of the light.

The wave model was also considered, but for this to be acceptable, the scientific method required the demonstration of the existence of the ether. So towards the end of 1800 two American scientists, Albert Michelson, Nobel prize for physics in 1907, and Edward Morley, proposed an experiment to demonstrate the ether's existence. Their idea was based on the consideration that the Earth, as it travels through space, must be subjected to an apparent wind from the ether, and being able to measure the speed of this wind would mean knowing the absolute speed of the Earth through space. Humans are not able to perceive the apparent wind of the ether, contrary to the light that is transported by the ether. According to this hypothesis then, if a light ray is directed in the same direction of the ether wind, it should travel faster than one that proceeds perpendicular to the ether. In the first case the speed of light is added to the speed of the ether but not in the second case. The following step would have been to measure the difference between the speed of light with the ether wind in favor or across. The experiment, repeated a large number of times in various conditions of measurement and with increasingly precise instruments, failed continuously so that they surrendered to the evidence and in 1887 they stated that the speed of light with respect to the Earth is equal in all directions (Michelson and Morley, 1887).

The Austrian scientist Ernst Mach, physicist and philosopher was one of the leaders of modern positivism, preaching for science to get rid of religious and metaphysical assumptions that for centuries had oppressed it, after learning the results of Michelson and Morley, came to the fundamental conclusion that the speed of light is equal in all directions because there is no ether wind and therefore the ether does not exist. But if countless experiments and theories had confirmed that light phenomena had a wave character, then what kind of waves was light made of? For a long time, physicists dealing with electricity and magnetism had assumed that light and electromagnetism were closely related. In fact, electrical and magnetic forces, like light, could be exerted at a distance without the need for any solid, liquid or gaseous substance. To explain this it was necessary to resort to a new and fundamental concept: that of field of action of a force that can be gravitational, electrical or magnetic.

It was Michael Faraday who first highlighted the link between the oscillations of the electric field and those of the magnetic field and who, towards the middle of the century, assumed that light was connected with the propagation in space of these field (Faraday, 1851). In 1864 James Clerk Maxwell was able to give a theoretical basis to Faraday's experiences formulating a set of equations able to describe the phenomenon of propagation of electromagnetic waves in all its aspects. These are precisely Maxwell's equations, which have become the foundation of electromagnetism and modern optics (Maxwell, 1864). According to the theory of electromagnetism, light is an electromagnetic radiation with a wavelength between 380 and 780 nm where the pure colors of the rainbow correspond to monochromatic radiation of different wavelengths.

After Faraday and Maxwell it seemed that the theories about the nature of light were complete, so that scientists of that time thought that in physics there was nothing more to know. However, at the end of the nineteenth century, the debate reopened. In particular, two experiments challenged classical physics: the black body emission and the photoelectric effect.

The ideal blackbody is an object capable of fully absorbing light of all possible frequencies, transforming light energy into heat. Around 1850, the physicist Robert Kirchhoff discovered that a substance capable of absorbing certain light frequencies emits the same frequencies if properly heated and, therefore, following the physical laws of those times, if a black body is brought to high temperature it should emit light energy equally divided among all the frequencies (Kirchhoff, 1859). A few years later, the English physicist Lord Rayleigh, Nobel laureate in physics in 1904, proposed that intensity gradually increased with frequency. In reality, however, Kirchhoff and Rayleigh's predictions turned out to be wrong. In fact, another German physicist, Wilhelm Wien, Nobel Prize for Physics in 1911, analyzing the spectral emission of a black body brought to different temperatures, found that there was emission of all frequencies but not with constant intensity. The Wien experiment had therefore disproved any possible prediction of blackbody emission obtained with the theoretical assumptions of those times. The explanation of this phenomenon is due to Max Planck, Nobel Prize in Physics in 1918. He hypothesized that, contrary to popular belief, the probability of emission of an incandescent body was not the same for all frequencies but decreased as the frequency increased. Planck's theories were based on the hypothesis that light energy did not flow with continuous values but thickened in quanta or packets of light (Planck, 1914).

At the end of the nineteenth century there was news of another experiment that could not be explained by the wave theory of light. A German physicist, Philipp von Lenard, Nobel prize for physics in 1905, had discovered that a metal hit by a beam of monochromatic light emits electrons: this phenomenon is called photoelectric effect. In the experiment he noted that there was no emission of electrons when the incident radiation has a frequency below a certain threshold value, even with or very high light intensity. In addition, by increasing the intensity of the light beam the number of electrons emitted increased but the speed at which electrons leave the metal was always the same. In order to increase the speed of electrons, it was necessary to vary the frequency of light towards the violet or ultraviolet region. The wave theory of light fails to explain the results of this experiment. In fact, for the wave theory electrons can be emitted whatever the frequency of light, as long as it is of sufficient intensity. Also, contrary to experience, wave theory predicts an increase in the velocity of emitted electrons as light intensity increases.

The one interpreting this phenomenon was Albert Einstein, Nobel prize for physics in 1921, who resumed and expanded the hypothesis made years before by Max Planck on black body emission. According to Einstein, not only energy exchanges between radiation and matter occur in a quantized manner, but the same radiant energy propagates in space grouped in many packets called light quanta or photons. The photoelectric effect can be interpreted as a collision between photons of light radiation and electrons of matter; in this collision an electron, hit by a photon, can absorb its energy. For the photoelectric effect to occur it is necessary that this energy, transported by the photon and absorbed by the electron, is at least equal to the work needed to extract electron from atom. As the intensity of light radiation increases, if the frequency is kept fixed, the number of incident photons increases and therefore the number of emitted electrons, but not their energy. Thus, the light quantum hypothesis provides a satisfactory model for the interpretation of the photoelectric effect (Einstein, 1905).

The work of Planck and Einstein had the merit of clarifying the nature of light: it has both wave and corpuscular aspects. There are phenomena that can be explained with both theories such as the rectilinear propagation of light, while the phenomena of interaction of light with itself, such as interference and diffraction, are interpreted with the wave theory. On the other hand, the corpuscular theory is better suited to explain the interactions between light and matter.

The seemingly irreconcilable contradiction between corpuscular and wave theory of light has been clarified, and formalized in the twenties, by physicists Werner Karl Heisenberg, Nobel Prize in Physics in 1932, and Erwin Schroedinger, Nobel Prize in Physics in 1933. This marked the birth of quantum physics, an essential tool for the treatment of atomic processes. With it we can also study large-scale phenomena, although the results to which we are led are not very different from classical or Newtonian physics. With these hypotheses, Newton's old idea of luminous corpuscles comes back into play, although we now refer more to agglomerates of energy than actual material projectiles.

1.3 Light from physics to visual perception

It is also thanks to theoretical studies of light that artificial light technology, which has developed from the late 1800s to the present day, has changed the human perception of the relationship between the Sun, now considered a small star in the infinite universe, and light. In fact, light now exists even without the Sun, so the styles and rhythms of life have changed accordingly. The Sun is synonymous with health, the outdoors, clean energy but also, unfortunately, harmful ultraviolet radiation (de Gruijl, 1999). In some cases, excessive sunlight must even be made more controllable and modifiable to facilitate work and leisure activities. The continuous and constant development of artificial light sources has led to a radical change in the image of the city in the evening and night hours, but also to the possibility to illuminate, on command or automatically, residential and working interiors, meeting, leisure and socialization places. Artificial lighting has become a consumer good and is a distinguishing element between modern and primitive societies. The cultural, social, scientific and technological development of modern society is closely related to artificial light. Light can provide simple visual signals but also convey more structurally complex information, such as reading a book or digital screen.

In order to be stimulating, artificial lighting must not be obsessive and homogeneous, like the aseptic one created by electrical installers in the slavish respect of the old norms, but it must rediscover the variability and changeability of natural environments, respecting colors and the fundamental value of shadows, as well as the artistic values linked to the use of light as an instrument of artistic representation.

The colors and shapes we see are an inner perceptual projection of the real world (Zeki, 1993). Light transmits this information to the receptors in our visual organs. If an object appears red to us, it is because it reflects light of a certain type. If it appears spherical instead of cubic it is because the variation of luminance of the light, reflected from the surface, allows us to elaborate at a cerebral level the perception of the variation of the distances of its parts from our eyes (Gregory, 2015).

With regard to form, we can also note that the visual perceptual sensation can also be confirmed by touch; at least two different senses can comfort us about the material nature of things. With regard to color, we can't say the same. In the reality of physics, objects are not colored and light has no color. For over a century we have been knowing that light does not have chromatic characteristics but rather electromagnetic spectral characteristics or, according to an even more modern theory, it is formed by photons: tiny wave packets that in some cases behave as corpuscles and in others as waves. Color is a psycho-perceptual sensation that our brain processes according to the spectral characteristics of the light information it receives from the surrounding environment as a whole. If a surface appears yellow to us, it is because it reflects light by modifying its spectrum according to a precise law of reflectance, with respect to the surrounding context. The perception of this spectrum will produce the sensation of yellow in our cerebral cortex. However, we cannot have any evidence that the same light spectrum produces identical colorimetric stimuli in two different subjects. Just as we don't know if the person sitting next to us perceives the world, with the various senses, exactly as we do. Associating the perception of a given spectrum with a color and name, yellow, is something we are taught in our childhood, it is related to our cultural development.

Having accepted the association between the spectrum of light, the perceived chromatic sensation and the name that we give to a color, the question arises: why do we want to distinguish between chromatic and spectral characteristics? The reason is that the human visual perceptual system does not behave as a simple measuring instrument, associating colors to spectra, but it rather interprets spectral information within a given context and, from the analysis of the information received, produces the color sensation. Evidence for this claim also comes from the introduction of artificial light into human activities.

Sunlight, which we generally consider white, has an energy content distributed fairly uniformly over all wavelengths of the visual spectrum;

these, perceived separately, are the fundamental colors of the rainbow, the pure colors. With natural lighting we perceive objects with colors such as yellow, blue, red, green and all the intermediate hues, but also the magenta hues that do not exist in the rainbow. If we illuminate the same objects with the classic tungsten filament incandescent bulb, we perceive the same colors, perhaps slightly yellowed, but we are still able to distinguish them. However, the light spectra reflected from the same objects under the two different types of illumination are substantially different. The spectrum of light reflected from a surface actually depends both on its material and on the spectrum of incident light. Additionally, it is known that, unlike sunlight, incandescent bulb light emits little radiation in the blue and green spectral regions and much more in the yellow and red spectral regions.

How then can the brain produce similar color sensations in the presence of substantially different light spectra? Visual perception is an open research topic worldwide and much remains to be discovered. Some believe, however, that the reason for the human ability to compensate for the dominant colors, due to different illuminating spectra, is a factor developed with evolution, as the best possible tool to distinguish objects, colors and dangers, in the struggle for survival under all types of natural illumination: from direct sunlight to that filtered by the green in the dense forest, to the night light of the moon or torch fires. Edwin Land, founder of the Polaroid Corporation, presented a theory according to which we do not distinguish colors by directly assessing perceived light spectra, but rather by comparing them instantaneously with the entire context in which they are perceived (Land, 1977). This comparison operation makes it possible to greatly attenuate the chromatic dominance due to illuminance, since this component is uniformly distributed over all the perceived surfaces.

1.4 Lighting vs exhibition

The incredible influence of lighting on people has been known since the days of classical theater. Still, the advent of artificial lighting made it possible to bring the impact of light to levels never reached before (Schielke, 2019). A striking example of the use of electric light in a scenic context of propaganda was the well-known "Cathedral of light." In 1934, at the Zeppelintribune in Nuremberg on the occasion of the Reichsparteitag (the annual meeting of the Nazi party), Albert Speer, Hitler's trusted architect, used 152 searchlights with a diameter of 150 cm, loaned by the Luftwaffe to outline the frame of the immense stadium capable of host over 340.000 people. The effect obtained left the ambassadors of other states astonished (Speer, 1970), and the joint use of

Richard Wagner's music, Die Meistersinger von Nürnberg, was what consecrated the power expressed in that event (Moller, 1980). More than the political content of the parade, it was the synaesthesia between light and sound that forged the message of hegemonic power that would soon become sadly known to the whole world.

Later, the introduction of color in lighting in entertainment events is already documented in the postwar period in British theaters (Applebee, 1950). It even hypothesizes using these experiences to evaluate the quantity and chromaticity of light for the commoners (Strange and Hewitt, 1956).

The study of the relationship between illumination and stage in show events intensifies until it is finally formalized in 1970 (Reid, 1970). Time passed, and technology evolved, and in 1980 the moving lights were introduced to the market by Vari-Lite. The use of color becomes more and more important in live performances, until, in 1988, the concerts of The Wall by Pink Floyd, designed by Mark Brickman, traced a milestone for the lighting of shows (Williams, 1988). Since then, technology has made great strides in live performance, and manufacturers have incredibly evolved the luminaires from those that were once used in the '80s in discos.

However, thinking about the most expressive form of lighting design, that of the stage show, which influences the culture of design, numerous issues must be taken into consideration.

Lighting design for on the stage is not a simple task. Thinking of it as a series of operations that lead to a result, it could be possible to compare it to an artistic or architectural activity. Despite the freedom granted to the designer, numerous factors make the lights' preparation for a stage show an actual race against time and, obviously, technology.

Designers are today faced with the need to prepare and test everything before the installation. Working experience is essential in these cases; beyond the ability to find optimal solutions to possible unforeseen issues, knowing the venues where the lighting is required could be a big help for the lighting designer. Software tools such Lighting CAD and live Wysiwyg can somehow help to simulate the lighting installation. Still, as regards their use, there are different opinions on the part of professionals. Few avoid these systems entirely; others use them in the early phase, while others use them more widely. These are mainly software packages that allow the professional to virtually rebuild the place and virtually install existing lighting systems. However, the algorithms used by these software tools are not always very refined. Sometimes, the simulated venue does not have enough correspondence with the result.

The lighting designer's artistic sensibility remains the essential tool; knowing how to read the venue's various nuisances and visually transpose them, improving their emotional charge.

In addition to the venue's timing and the architectural characteristics, there are other external variables to consider. When outdoors, the event can begins while the Sun has not yet entirely set. Therefore, the luminous envelope evolves throughout the exhibition, and it is necessary to tweak artificial lights to adapt to the transition. These changes in the natural light atmosphere's color depend on numerous factors; place, season, time, and weather conditions. These are almost always variables that must be evaluated before.

Another element that can significantly influence the Lighting Designer's color choices is the light deriving from other element of the project: the now constant presence of LED-walls sources that put in scene digital content not always managed directly by the lighting designer.

In addition to external factors and variables, typical elements of the lighting design usual creation have to be considered. Even just the type of engagement of the lighting designer with the client, other figures in the design process teams, and new technologies ,which obviously imposes some constraints, can affect the professional's freedom of choice. These constraints may not be huge, but they usually happen; in this case, the designer must mediate them with his vision of the project.

With the advent of LED sources and IoT, technology of lighting devices continues to improve in years, providing more possibilities every day: higher powers, more control, and bright full colors. However, the flip side of the coin is that as the possibilities increase, so does the complexity (Siniscalco, 2021). If we think of the lighting design of just some years ago, everything was about using fixed white luminaires; flexibility was less, but the design process time was lower.

At the extreme side of new exhibition lighting, moving lights allow an extensive range of colors to be obtained, gobos to be implemented, light to be profiled to remote control them, as new luminaires are potentially able to carry out different lighting performance. Technology increased flexibility to a level that that was unthinkable until not long ago, but such improvements can be overwhelming for the designer. The possibility of obtaining unlimited colors does not necessarily mean that this should be done. This consideration does not mean that technology should be avoided. On the contrary, today, more than ever, it is essential that professionals are prepared for the possibilities that products and systems have to offer, always keeping up to date to evaluate the best choices.

Figure 1.4. A modern moving light produced by Claypaky (an Osram business). The HY B-EYE K25, in addition to the typical features of motorized luminaires, allows the control of every single LED, allowing countless kaleidoscopic projections.

Concerning advanced light sources, solid-state lighting has conquered its position in the exhibition and more in the architectural lighting field. The possibility to contain the power implied has LED manufacturers develop many devices that mount this type of source.

Regarding hues, LED light sources can produce more saturated colors, not in terms of the color rendition of illuminated materials, but the light beam's appearance, when projected into the environment. In terms of entertainment, the color white remains a weak point of LEDs, sometimes it is still less brilliant than the one created with metal halide lamps. Some LED sources are offered in RGBW format (Red, Green, Blue, and White) to give greater chromatic flexibility, but the result is still not comparable with some discharge lamps from a white point of view.

1.5 Lighting and color for TV and Cinema

Lighting for television and cinema has a very ancient history. Around the one century ago, the use of artificial light in indoor studios instead of outdoor theaters led to a revolution of light in scenography, giving the great masters of photography a whole new ground in which to experiment. One of the most notable masterpieces that made this experiment the key to his success was Fritz Lang's Metropolis. In this movie, light assumes a semiotic value, in the management of light and shadow, in the dynamic projections, using electric discharges and luminous objects as scenographic communication tools to amplify the scenes' affect human emotions (Roth, 1978). Lang drew his inspirations from Art Deco, Bauhaus, and Futurism (Rutsky, 1993; Wolfe, 2020) applying them to light. On that occasion, the design of light went from a scientific and technological subject to a communicative, scenographic expression (Pooky, 2016).

The first and foremost difference between TV and cinema lighting is that the illumination must meet the requirements also for the cameras than the human observer. Even if sophisticated, these devices do not have the typical processes of the visual system. Some technologies may attempt to copy some visual system features; however, the complexity of human perception cannot be easily replicated, and some corrections are necessary.

Concerning color, the immediate attention that the lighting design group must have is to apply all the necessary technical procedures to balance the CCT of all the light sources on the stage. It is fundamental to carry these procedures following the white balance for digital cameras or stock of film chosen.

A second fundamental task consists of introducing colored light for aesthetic reasons or simulating specific light sources in the scene to support the program's narrative.

Speaking of the world of cinema and television lighting, we can report that some importance is given to the CIE 1931 chromaticity diagram. This diagram, presented in details in a following chapter of this book, represents the gamut of human visual perception. The colors all appear in their most saturated version on the outside of the horseshoe. Of these colors, the most peculiar ones lie on the line of the purples, which represents colors that are obtainable only through the mixing of the extremes of the visible spectrum. The most interesting component, however, is the one given by the central space of the diagram. That is where the color saturation decreases until it reaches the curve known as the Planckian locus, which represents the whites in their various shades, namely the CCT.

Warm light to cold light, commonly measured in Kelvin, is well known and widely used in workplaces' lighting. Still, the problem linked to this aspect, in the TV-lighting field, is considered from a different point of view. When lighting sources with multiple color temperatures are present simultaneously in an environment, the human visual system tends to mitigate the dominant colors by attenuating the perception of different colors; the light will appear warmer or colder but still white.

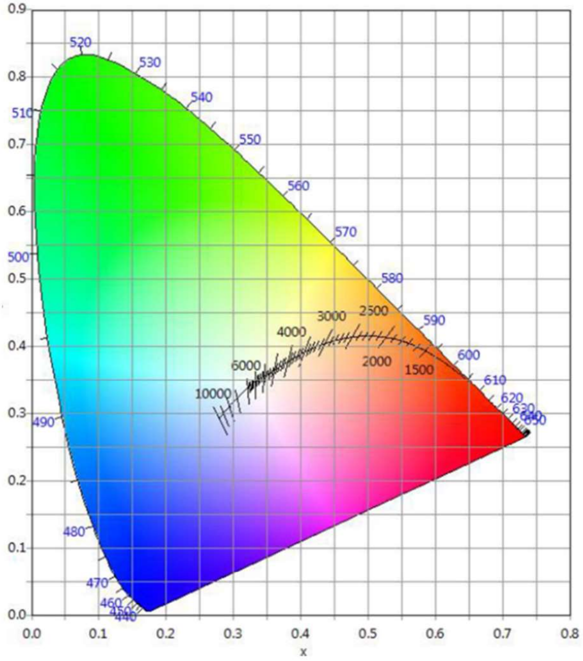

Figure 1.5. The CIE 1931 chromatic diagram.

This phenomenon does not apply to equipment such as cameras. Whether they are film stock or digital sensors, both Charge-Coupled Device and Complementary Metal-Oxide-Semiconductor, they are not equipped with the sophisticated correction methods typical of the human visual system. They might have attenuation algorithms, but they will never be at the level of our visual perception. Stock films, for example, are balanced at 3200K (Tungsten light) or 5600K (Daylight); digital cameras, on the other hand, can be set to a value of your choice between 3200K and 5600K, but always and in any case only one CCT at the time. This means that when there are whites with different color temperatures simultaneously in a scene, the camera can only have a single white point as a reference; the others whites will all appear more or less yellowish or bluish.

This situation is not acceptable when it comes to TV or cinema recordings, and therefore, once the reference white has been established, some correction operations on the sources must be adopted. On non-dynamic light sources, it is possible to operate additively by summing other sources with different color temperatures to balance. Alternatively, it is possible to use subtraction, reducing the power of some components of the spectrum. This result is usually obtained (at least partially) employing correction gel filters named Color Temperature Orange (CTO), or Color Temperature Blue (CTB). Filters have different intensity levels and are designed to shift the light along with the Planckian location. LED light sources can modify the shade of white and colored light, with multi-chip sources or luminaires with different phosphor panels. However, it is not uncommon to use filters even on solid-state sources; general lighting designers sometimes use this technique in specific fields such as the exhibition area (Murano, 2015).

Solid-state light sources have now also taken root in the entertainment lighting sector. The efficiency of these sources is undoubtedly a plus for anyone; however, one of the main reasons why LED technology is particularly desirable (now that the emitted fluxes have become more than reliable) is the possibility of controlling numerous parameters of every single luminaire remotely. Indeed, some aspects will take some time to be accepted, such as comparing LED with high-power HMI sources; the latter are more available and less expensive for the same luminous flux. Still talking about economic aspects, the productions are often reluctant to invest in something that provides the same visual achievement that was obtained with classic sources, looking only at the final result and not at man/hours and better management control processes. Finally, the irruption of electronics in a field historically dominated by electrical engineering leads to the need for staff improvement, introducing skills that were not widespread before; this requires a lengthy training process that often slows down production in a sector where timing is essential. In addition to the difficulties described above, there are other aspects to take into consideration. The advent of LEDs has enriched the color palettes of directors of photography. Numerous ways of standardizing color coordinates have been studied to have a common vocabulary. However, this made it even more evident that different cameras capture color in a slightly different way from each other. In addition to this, the reproduction of captured colors is done on devices, the user TV screens, that often have inadequate gamuts. The light color can be created by adding different types of LEDs or by conversion using phosphors. In order to complicate things, these two approaches can include several methodologies and other elements. In the various steps necessary for video reproduction, metameric matches can frequently happen that, with the classic sources were less common. In some aspects of the production, a high color rendering is desirable: make-up, wardrobe, brand identity, commercial products, logos. Their reproduction must not be distorted by light sources that are inadequate from a spectral point of view. Numerous efforts have been made to find a way to describe the ability of a light source to render color; the color rendering indexes have existed for several years. However, they present some fundamental problems that make them unsuitable for the television and cinema lighting sector.

1.6 Social tasks and professional profile of the designer

For four decades, the Politecnico di Milano has hosted a line of professional, but also scientific and cultural training, which has set itself to evolve the science, knowledge, and skills of the historical figure of the lighting engineer to the modern figure of the lighting designer (Rossi, 2008). And in more recent times a training course has also been launched, on the still less known, color designer (Rossi *et al.*, 2016)

Until the '70s, the lighting engineer was a niche technical figure, with a degree in engineering or physics, more often a graduate or frequently self-taught, with tasks of performance optimization for lighting plants and systems managed by electric companies and lighting fixtures produced by industries in the sector, at the service of collective users, related to the world of services and work. The skills of this figure were only rarely taught in universities, and in these cases were related to the scientific field of environmental physics, with the teaching of lighting engineering, a subject matter currently active in sporadic courses held by a few universities.

Starting from the 80's, aware of the role that light had in the cultural system of the project, with the practices of art, architecture, design, urban and environmental planning, a long path of cultural and disciplinary renewal has been promoted. This led the Politecnico di Milano to start a didactic experimentation within the Faculty of Architecture and then to develop it within a new Faculty, today the School of Design, shifting the scientific axis from exclusively technical-engineering disciplines to design ones, and gradually focusing, both culturally and professionally, on the figure of the Lighting Designer, in both its design fields, mutually integrated and synergistic, the Lighting Designer and the Lighting Product Designer. Today, the latter must also deal with the new technologies of solid-state lighting, LEDs, and with the application of colored lighting, which is no longer relegated to fairs and amusement parks, but finds a new position linked to well-being, in interiors, and to temporary communicative set design, in urban spaces.

With the first postgraduate course in "Lighting Design" activated within the Faculty of Architecture, entrusted in 1978 to the direction of Marco Zanuso and then to Alberto Seassaro, a long phase of didactic experimentation was initiated which progressively produced, at first, numerous courses in Lighting Design, related to the scientific disciplinary sector of design, within the degree courses in Architecture first and then within the degree course in Industrial Design. Subsequently, an organic branch of light design was established within this course of study, with a three-year learning path that ended with company internships and dedicated dissertations, to arrive finally from 2003 to the Master in Lighting Design & Technology of the Politecnico di Milano, initially directed by Alberto Seassaro with deputy director Maurizio Rossi and since 2010 directed by Maurizio Rossi. The Master is entirely taught in English and is unique in the world in that it is also held in a research laboratory, the Luce Lab of the Politecnico di Milano, active since 2002 at the Department of Design. In these years of teaching and didactic experimentation, but also of scientific research, experimentation and technological transfer, more than a thousand of people, practicing the profession of Lighting Designer or working in companies and institutions in the lighting sector, have emerged from this multi-year training experience. The wide diffusion of these professional figures and the full recognition of the cultural, social and economic value of this field of study and research, required to define the specific figure of the Lighting Designer.

The more general scenario surrounding the Lighting Designer is that of a mature society, affected by rapid and profound transformation processes, which must deal with environmental imbalances caused by pollution due to production processes, but also with the impact of non-renewable energy sources. The improvement of the individual and social quality of life must necessarily measure itself also with the aspects of visual comfort, not only with the limits imposed by lighting technologies, but also, and inevitably, with the problems of environmental nature (Peña-García, 2020). In fact, the increasingly pressing environmental issue leads us to take into account all the issues related to the proper use of energy resources and materials, in the search for design solutions that enable the use of renewable materials and a decrease in electricity consumption, both in the production and distribution phase, as well as, and most importantly, in the operation of large lighting systems of public and private places (Rossi, Siniscalco and Zanola, 2009). Also the territory, in its various structures, think of urban centers with high building density and large metropolitan infrastructures, is marked by artificial light, often used incorrectly, without the necessary in-depth studies and design elaborations on the biological impact (Gaston, Visser and Hölker, 2015). The continuous and pressing call, by astronomical observatories, for the containment of the deleterious effects of light pollution, which is constantly increasing and prevents the observation of the skies at night in the vicinity of population centers, should make us reflect on the frequent episodes of bad and excessive lighting, in many cases the result of the poor standardized methods of calculation for the sizing of the systems (UNI, 2021). A more attentive lighting can be achieved with a more correct methodology based on the integrated analysis of all aspects that contribute to the determination of the optimal distribution of light in the spaces, from light sources to the reflectance of building materials, up to differentiated hourly flows for the finalization of primary visual tasks changing over the twenty-four hours (Wright *et al.*, 2013).

As a basic environmental factor to extend, beyond daylight hours, the use and enjoyment of public and private spaces, artificial light plays a decisive role in the construction of living spaces in modern society. In the interiors, the daytime use of natural light is today increasingly under review, with the study of solutions integrated with artificial light, in order to obtain levels of illuminance that meet the ergonomic requirements of visual comfort, established by the standards of the sector and according to the changing climatic, seasonal and daylight conditions of natural light (Boyce, 2010). The interior designer has always been a well-defined figure characterized by professional skills different from those of the architect, who works on an architectural scale. This figure must have skills in the field of design, as well as an in-depth knowledge and the ability to design furniture and interior design products, putting in relation the different objects to each other, to the space, the light that embraces them and above all the human activities. The interior design training must address all aspects of this discipline: the design of domestic environments, the design of workplaces and urban settings, the exhibit and museum design, while trying to develop an awareness of the problem related to the management of light and how it can affect the perception of living spaces.

However, the reality of Lighting Design presents problematic aspects that require research and experimentation, in the design method and in the way of dealing with the relationship between humans, light, spaces, shapes and colors, in all their facets and technical, productive, environmental, social and cultural implications (Castiglioni, Baldacci and Biondo, 1991). Lighting Design, as illustrated above, is a design process that cannot take advantage of the rapid and/or scale prototyping tools commonly used by designers. Problems with a technological, but mainly a perceptive nature, prevent the creation of scale prototypes of lighting projects that could be of any use for a correct evaluation of the quantitative and qualitative aspects of natural and artificial lighting.

The design of light requires operators capable of linking together the perceptive, technical, economic and socio-cultural dimensions, and starting from there to propose new design syntheses. In this context, the most relevant changes are to be found in the technological innovations represented by new light sources, new materials-colors and innovative tools that computer graphics and IoT can make available to support the lighting design process. Lighting CADs enable the management of virtual project models simulating the physical reality of lighting, thus introducing a virtual prototyping tool into the lighting design journey. The advantages that virtual prototyping tools can offer in Lighting Design are countless, from low costs to the simple possibility of doing something that is not otherwise possible and, additionally, the enormous educational value that they can have in the training of Lighting Designers. Only with these tools it is in fact possible to combine the direct teaching of a subject matter with a strong scientific and technological content, with the possibility of an easy virtual practical experimentation of the fundamental assumptions and design applications.

Another consequence of these technological innovations is the increasing importance that project communication can take on. This requires a consistent integration of the calculation methodologies and techniques with those dealing with representation, typical of visual communication in the field of design, in which the visualization of the objective data of the project is combined with virtual photographs aimed at a subjective evaluation of the appearance of the project. Often in the project, due to the absence of prototyping tools, objective photometric measurements and subjective quality evaluations (Veitch, 2001) are carried out in the field only at the end of the implementation phase of the lighting system. On the contrary, virtual prototyping tools make it possible to insert this phase at the center of the design process, thus providing an innovative tool for intermediate evaluation of the expected results, according to the project specifications, as well as the possibility to easily rework various types of different or variable solutions according to changing visual tasks.

Virtual prototyping of lighting also enables a photorealistic three-dimensional approach to the study of visual communication and advertising strategies, for the realistic simulation of light-based communication structures, and also the production of digital media on the new fronts of multimedia communication, in the numerous applications of interactive and hypermedia design as well as the design and production of digital videos.

1.7 Conclusions

In this introductory chapter, historical, cultural, and scientific elements were introduced on the theme of the relationship between human beings and lighting, with the aim of channeling these themes into the lighting designer profession. The subject matter is wide, from a cultural, physical, and technological point of view. Still, the approaches are significantly different, as are the terminologies and tools. This does not mean that there is a discriminating factor to boast the title of lighting designer, freely used both in the traditional lighting world and in entertainment. Attention must be paid to the differences that characterize the various sectors, approaching novelty with an open mind to better understand various professional sectors. Overlaps, technologies involved, tools used, final goals to be pursued, and the means to achieve them. Being able to understand the design approaches of the various professional fields could allow tackling every project, the lighting of buildings, shows, installations but also retail, workplaces, etc., drawing multidisciplinary inspiration, to obtain a final result which technically adequate, but also able to inspire those who experience it.

1.8 Conflict of interest declaration

The author declares that nothing has affected his objectivity or independence in the production of this chapter. Neither the author nor his immediate family member has any financial interest in the people, manufacturer or topics involved in this article. The author also declares that no conflict of interest, including financial, personal, or other relationship with other people and organizations, could inappropriately influence, or be perceived to influence, this work.

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Chapter 2

Innovation and lighting design work

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Abstract

This chapter focus the attention on the ways in which artificial electric lighting has changed over the past century. It also analyzes the leading areas of research and development in the field of lighting and the consequent areas of intervention of the Lighting Designer in a period, such as the current one, of strong innovation in tools and methods. Today's lighting project requires operators capable of effectively connecting the perceptive, technical, economic, and socio-cultural dimensions and of starting from here to propose new design syntheses. In this context, the most relevant changes are to be found in methodological and technological innovations, represented by international standards, new light sources, and innovative tools that information technology (IT) and the Internet have made available to support the process of lighting design.

Keywords

Lighting design, CAD, BIM, lighting standard, IT

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2.1 Introduction

Since ancient times, in the history of human constructions, the presence of light has influenced and been an integral part of the development of the design to help shape the functional and artistic aspects of structures. In the Roman Villa, the center of activity took place around the impluvium where natural light, direct from the sun or diffused by clouds, penetrated and then spread into the adjacent living spaces, which had almost no windows. The purpose of the impluvium, apart from collecting rain, was to capture and diffuse the light inside the house. In the Middle Ages, the different historical and cultural situations saw an example of the use of light in the large polychromatic windows of Gothic cathedrals, where colored light rays helped to create a mystical and imposing atmosphere of the structure. At the same time, in residential spaces, little attention was paid to light, as if to emphasize the obscurantism and closure of an era in which the need to protect the occupants from the outside prevailed. During the Renaissance, the need for fortification and defense of living spaces finally faded away, leaving room for the development of windows facing outwards, towards the street in urban centers, and inwards, overlooking a courtyard used as a vegetable garden or formal garden, according to social status. This openness to light on both external fronts of the living space reflected the cultural and social development of the time; heavy metal gratings still protected the exterior entrances, and in many places, this is still the case today. Since the Renaissance and until the advent of artificial light, windows were closely related to functions of the various interior spaces in architectural design. On the lower floors, large openings allowed more light to be captured, also in the presence of adjacent buildings. Upstairs (and down in social status), windows became smaller due to the presence of more natural light. The furniture arrangement within the individual rooms was aimed at using the natural light coming from the windows according to the various visual tasks: activities such as sewing and reading were organized near the windows. In contrast, other activities took place in more internal and darker room areas.

Towards the end of the 18th century, gas lighting became widespread in Europe in the most important areas of the most populated centers. This technology replaced the dim public lighting that until then had been achieved mainly with torches and oil lamps. Before the advent of electricity, artificial lighting was still based on devices that produced a limited luminous flux. Attempts to increase the illumination capacity were met with problems of fuel supply, heat development, oxygen consumption, and the practical impossibility of conveying and directing its light flow. Candles were costly and reserved for use on special occasions by the wealthy classes.

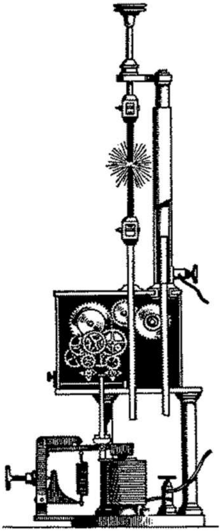

Figure 2.1 – Arc lamp with clockwork mechanism for the automatic regulation of the consumption of the electrodes.

In the 19th century, the discovery of electricity and the development of the first arc lamps laid the foundations for the development of electric lighting, which would become widespread in the following century. In the urban centers of the time, the weak public lighting relied on oil or, instead, gas lamps. In Milan, on 18 March 1877, the first public lighting experiment with an arc lamp was carried out in Piazza del Duomo. To a significant scenic effect, all the gas lamps were switched off, and those present saw the electric light suddenly burst from the top of a tower and illuminate the square (AEM, 1993).

The Galleria Vittorio Emanuele in Milan was also illuminated in 1881. Still, the arc lamps used had a limited lifespan, and the carbon brushes from which the light sparked wore out and had to be replaced daily. Despite a series of technological improvements, arc lamps had several technical limitations, which were only overcome with the advent of incandescent lamps for public lighting in the early 1900s. In 1883, the inauguration of the opera season saw the electric lighting of La Scala by Edison, and in 1885 the municipality decided on public electric lighting in Piazza Duomo, Galleria Vittorio Emanuele, and Piazza Della Scala. However, the advent of electric lighting did not supplant gas lighting, which continued to be developed until it was abolished in 1924.

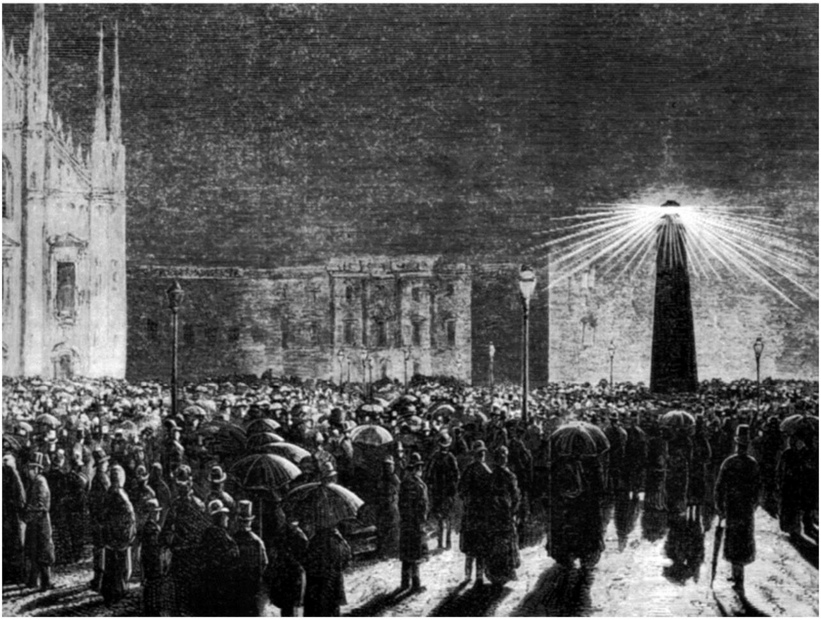

Figure 2.2 – The electric lighting experiment with arc lamp in Piazza del Duomo in Milan in 1887.

Interior lighting in the early twentieth century was divided between functional, essential lighting in workplaces and decorative, artistic lighting in the homes of the wealthier classes. The development of rationalist thought, and the relationship between function and form found a straightforward technological application in creating luminaires for workplaces; simple, essential forms of suspended luminaires aimed at projecting the flow of light into the area used for visual tasks. The same shapes can still be found in series production today.

In the decorative production of interior lamps, the new incandescent source was readily applied in the production of unique and valuable pieces, enriched by materials such as alabaster and mother-of-pearl combined with colored glass and gold silver-plated metals. The form was not induced by functional but by scenographic requirements, which take their cue from pictorial and sculptural productions as an expression of the artistic culture of the time. For many years and even to this day, the cheaper productions would continue to use forms from before the advent of electric light, such as the chandelier, the abat-jour, and the lantern.

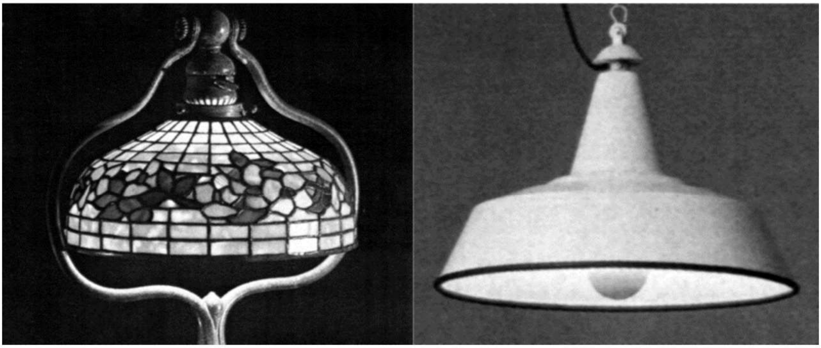

Figure 2.3 – Luminaires from the early 1900s. On the right, pendant luminaire for workplaces; on the left decorative luminaire for interiors.

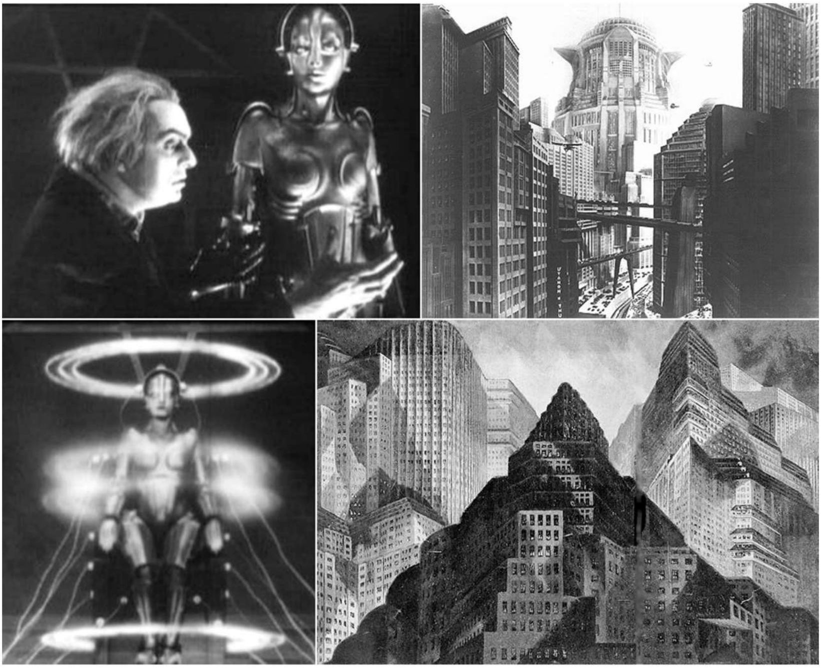

Figure 2.4 – The 1927 film Metropolis by Fritz Lang. Considered one of the masterpieces of world cinema, it was at the forefront also for the scenographically dramatic use of light thanks to a careful study of photography based on cuts of light and shadow that emphasized the halo of negativism of the industrial neo-culture.

The development of industrial production and the assembly line, activities that took place forcibly in closed environments, thanks to electric lighting, could achieve constant production processes independent of the geographical and environmental conditions in which these activities were carried out. The development of the service sector and office activities were facilitated by artificial lighting, as were commercial activities that, from the shop window to the vast superstore areas, had precise requirements for product display and the accessibility and safety of people.

However, until the 1920s, the efforts focused on the use of artificial light in public places were mainly aimed at scientific and technological research to improve the efficiency of lamps and luminaires for the production and transfer of electrical energy. From this period onwards, cultural sensitivity to lighting design as a fundamental element of architecture began to develop (Neumann *et al.*, 2011). More attention was paid to the effects produced on the human perceptual system by different types of lighting. Photography and Cinema also contributed in this regard (Bernstein, 2014). While still without color, it testified to the development of a greater sensitivity to the effects of black and white, the play of light, shade, penumbra and contrast, and the psycho-perceptive effects they induce on the observer. At this time, the ability of light to delimit spaces, contribute to scenography and emphasize the drama of a scene was experimented with.

Architecture has designed human spaces for thousands of years under one constant, natural light coming from above. Artificial light reversed this rule: at night, public lighting projected onto streets, and façades spread out from below and disappeared towards the top of buildings. Customs and lifestyles changed, the city also existed at night, and now its perception is fundamentally different from the daytime appearance or the ghostly atmosphere made of halos and shadows before the development of electric lighting.

The habit of such an elementary action as turning on a light with a switch, part of our everyday life for more than two generations, makes us forget that such convenience has been in the dreams of human beings for millennia.

2.2 Effects of research on lighting design

At the dawn of this product area, the incandescent lamp was a powerful and unnatural source compared to the oil or gas sources of the time. There was a strong need to tame it, make it safe, protect users from electric shock and heat, and obtain specific performances in the luminous flux emission. On the other hand, the luminaire acted as a mediator between the primary light source and the user of the lighting function.

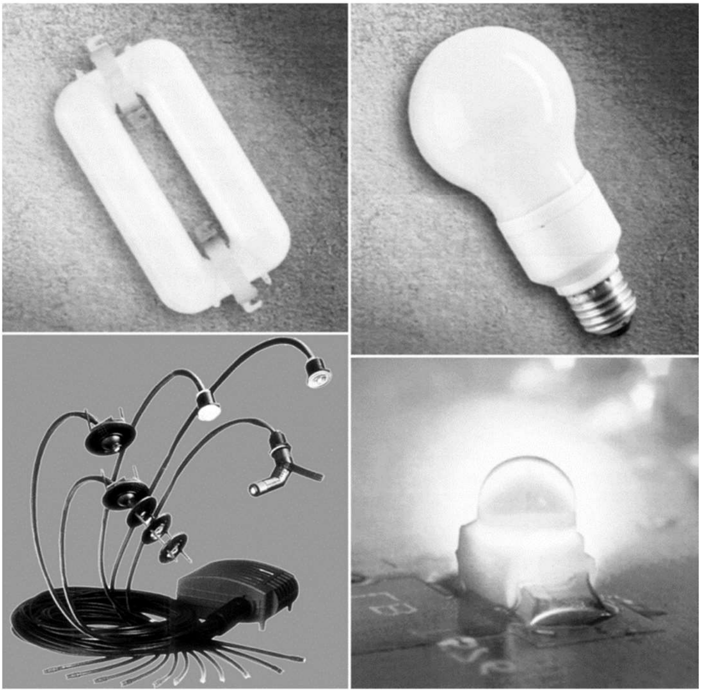

Figure 2.5 – Examples of light sources. Above an induction lamp and a compact fluorescent lamp. Below, a Philips system with light sources transmitted by optical fibers and a white light LED.

Research and development in the field of light sources and accessories are now focused on at least six main areas:

- Improved efficiency: lowering power consumption with the same emitted luminous flux. An incandescent lamp has an average efficiency of 13lm/W. This means that for every Watt of electricity consumed, it can emit a luminous flux of 13lm. Thus, a classic 100W tungsten filament lamp emits a luminous flux of 1300lm, while a compact fluorescent lamp can reach over 60lm/W and a new LED source can reach over 150lm/W (Xu and Chen, 2019).
- Increase in the average lifetime: hours of operation of sources. This ranges from the average 1,000 hours of old incandescent lamps to around 10,000 hours of compact fluorescent lamps and up to 50,000 hours or more of LEDs (Wang and Lu, 2014).

- The reduction of infrared (IR) and ultraviolet radiation (UV) emissions is harmful to living beings and many types of materials, particularly artwork.
- Improved visual comfort by analyzing aspects related to the ergonomic, evaluated today using the UGR factor (CIE, 2010), and color rendering of light sources (CIE, 2017; IES, 2020).
- Reduced size to better control the light output. In fact, by using reflectors or lenses to control the distribution of the direction of the luminous flux, it is easier to meet the design requirements of the luminaire the smaller the primary source is (Wu *et al.*, 2016; Yip, To and Wang, 2019). In the case of fluorescent lamps, we now have tubes with diameters of 38 mm, 26 mm, 16 mm, and only 7 mm in compact fluorescent lamps, with miniaturized electronic control gear. In the case of LEDs, the dimensions have been further reduced.
- Environmental compatibility: respect for the environment at all stages from production to use and end-of-life disposal of the light source. This is assessed in the LCA (Tähkämö *et al.*, 2014; Casamayor, Su and Ren, 2018).

Following these lines of research has led to the development of light sources and devices for various types of use, some of the main ones being:

- Compact fluorescent lamps with miniaturized electronic ballast integrated into the screw connection (Rosillo, Castejón and Egido, 2013). They have replaced incandescent lamps in many residential and decorative lighting applications with energy savings of up to 80% in some cases compared to the old incandescent lamps. This research has been carried out since the 1980s, for over thirty years, but today these lamps have almost been replaced by LED ones.
- Electrode-free fluorescent induction lamps have an average life of more than 100,000 hours (Wharmby, 1993; Hamady, Lister and Zissis, 2016).
- Optical fibers and light guides are used to direct illumination away from the primary source to allow greater control of radiation and heat as well as provide greater flexibility of use in lighting design (Deveau and Press, 2000; Logunov *et al.*, 2013) and convey the solar light (Lahiri *et al.*, 2018).
- LMS light management systems for intelligent electronic control of lighting according to various parameters such as daylight level, time of day, and prediction of the type of visual task required (Tsesmelis *et al.*, 2021).

- The innovation of solid-state lighting: LEDs, is progressively replacing all other lighting sources (Rea, 2010).

2.3 The players of lighting design

In the past in Italy, the design of luminaires was highly developed, as it was more accessible from the standpoint of the required industrial investments, compared to the high-tech design of the production of primary sources. In recent years, characterized by a severe economic crisis, companies in the lighting sector have been busy metabolizing the new lighting technology: LEDs, which have almost completely replaced other artificial light sources and changed the lighting industry supply chain (Highgate, 2015). LEDs are photo-electronic components, and lighting companies, which have been accustomed to working in the electromechanical sector for decades, have been compelled to acquire expertise in the electronics sector in order to continue producing luminaires (Meadows, 2018). This process, indispensable for the survival of companies, has absorbed most of the resources available for research and development.

Also important is the Italian cultural and artistic tradition, which finds in the design of the luminaire an application that is also infeasible in the design of light sources. It should be noted, however, that this Italian importance of good form is being undermined by those countries that have strategically invested in development, in the most complete sense of industrial design of the project, understood as coordination between the form, the integration, and the structuring of all the cultural, social, user-oriented, economic, constructive and technological factors that contribute to the definition of the production process of luminaires and systems.

In the last thirty years, the availability of increasingly technologically advanced sources and luminaires made it possible to turn the attention of Lighting Design more towards defining and achieving illuminance and luminance levels according to the various visual tasks established in the requirements phase. Following this logic thread, research has produced and continues producing technological advancements on several fronts: on the one hand, light sources manufacturers have improved the performance of their products in terms of efficiency and color rendering. On the other hand, designers and luminaire manufacturers are committed to designing and enhancing photometric properties related to the requested illuminance characteristics. Consequently, the Lighting Designer is an intermediate figure between the architect and the engineer and engages in research into the functional and perceptual aspects of lighting (Major and Speirs, 2006). The lighting project must therefore follow a multidisciplinary process that develops through the analysis of the volumes assigned or being defined, of the paths, areas, and materials that interact with the human actors who benefit from the lighting service, but also through the analysis of technical problems and the perceptive, physiological and psychological aspects of visual perception (Boyce, 2014).

Another sector that has benefited from the results of research in lighting is visual communication. Research in fields such as security, communication, Cinema, and multimedia, which in today's society form the basis for the conveyance of information, could not ignore the influences arising from the potential of artificial lighting as the primary tool or medium for capturing the attention of observers (Schielke, 2010). Video projections, light effects, colors, contrasts, stroboscopic effects, and many other devices are increasingly being tried out and used to support visual communication and shows.

2.4 Research centers

In a sector such as artificial lighting, where the stimuli produced by scientific and technological innovation are omnipresent, research has led to continuous improvements in design tools and methods. In Italy, unfortunately, the studies with a high scientific content have not developed as they have in other countries, since they are not directly applied in production and design because of the high investments needed for development and also because of the lack of a business dimension capable of bearing the costs. On a global level, however, thanks also to the far-sightedness of social and organizational systems that base the primacy of their economic system on investments in research, the technological development resulting from theoretical studies has led to a continuous improvement in the production of light sources, improving their color rendering and efficiency. In addition, in the field of materials, research has produced technologically relevant and cost-effective results for optical applications thanks to the introduction of plastics and carbon fibers.

At a global level, research has seen significant contributions from institutional bodies such as universities, government research institutes, and industry associations. The Lighting Research Centre of the Rensselaer Polytechnic Institute is one of the most advanced centers for research and, above all, for the dissemination of lighting technology. Its website provides free access to a wealth of information on current research in various fields, including lighting design criteria for the elderly and for health protection, new types of light sources, the relationship between natural and artificial lighting and sensors, and an extensive bibliography on the subject.

A historical example of the result of research in terms of luminaire innovation is the Sivra produced by iGuzzini, whose Centro Studi e Ricerca developed a system for automatic variable control of color and lighting level in 2000; as well as contributing to other research into the development of technologies and related equipment to enable the capture, transport, and diffusion of natural light for the interiors of buildings aimed at the well-being of workers (Centro studi e ricerca iGuzzini, 2007). Also of interest are the contents offered by the Canadian National Research Council's Institute for Research in Construction, which presents a great deal of research on lighting design aspects in construction. The Illumination Engineering Society of North America (IESNA) is a source of numerous standards and recommendations, some of which are accepted worldwide.

There are few public centers for design research on lighting systems for different kinds of applications in Italy. The Laboratorio Luce of the Politecnico di Milano has been operating since 2002 on lighting engineering, colorimetry, visual perception, and lighting design at the Milan-Bovisa site. In Turin, on the other hand, as part of a research project co-financed by the MURST, a project for a lighting research and experimentation center (CERSIL) was developed at the beginning of the 2000s at the Politecnico di Torino, aimed at research into natural and artificial lighting and visual comfort. There is also the Laboratory of Photometry and Lighting Technology at the University of Naples Federico II that performs measures for assessing the quality of natural and artificial light in relation to both energy saving and ergonomics of vision. They deal with artworks' lighting with specific studies on exhibition and conservation with models, monitoring, and simulations.

2.5 Indoor vs. outdoor

Research has shown that in lighting design for exteriors, many issues are amplified compared to interiors. The installations must guarantee adequate lighting levels for safety and/or scenic purposes while at the same time reducing energy consumption and avoiding light pollution, i.e., the dispersion of light towards the sky.

Technological developments in light sources and luminaires have made it possible to increase the efficiency of lighting installations even in unfavorable environmental conditions and reduce the amount of maintenance required. The maintenance costs of an installation are one of the variables that the designer cannot absolutely ignore, but rather must highlight and, in many cases, are one of the project's specifications, carrying out measurements and research on natural and artificial light (Marsden, 1993; Perry, 1999).

In outdoor lighting, technological innovation as a result of research has progressively led to the definition of new sources and lighting fixtures, the definition of lighting standards for personal safety, and the study and definition of proper lighting for road traffic.

In the course of the 20th century, there was a gradual shift from models of light sources placed on lampposts at the sides of roads for traffic and pedestrian safety to light sources suspended in the middle of the road and focused more on lighting vehicular traffic than on pavements. Nowadays, thanks to new LED sources and the possibility of controlling the flow of light more precisely, pole-mounted lighting fixtures have regained a prominent position in urban and vehicular lighting. In fact, the subject of lighting for vehicular traffic, both urban and extra-urban, has become an almost independent area of research. In this area, the many aspects of design are strongly influenced by the need to increase the degree of safety of road traffic. Worldwide statistics and research have amply demonstrated that the number of accidents is drastically reduced by the quality and effectiveness of road lighting (Raynham *et al.*, 2020; Fotios, Robbins and Uttley, 2021).

In Scandinavia, street lighting systems are being tested, which switch on instantly, providing maximum flux only when a vehicle is present and following it along the road (Mclaughlin, 2018).

The sector of monument enhancement, combined with strategies for the recovery and conservation of the existing building heritage and cultural assets, has also witnessed the consolidation of greater attention towards a culture of light. This aims to create scenic effects through the study and research of the most appropriate lighting techniques for the various and numerous types of cultural assets of our country. Light can enhance a given cultural site and make it appreciable for a broad audience. However, as research has shown, it needs to be controlled to avoid becoming a further degradation element (CIE, 2004; CEN, 2014).

Therefore, the focus of research is also on how artificial lighting can become an essential complement in the design of indoor and outdoor spaces. In coordinating the various artistic and communicative elements with usage needs, it is necessary to determine which tasks to entrust to light and which results are to be achieved. Light can induce a spatial alteration in perception, making a part stand out from the whole through the projection of shadows and contrasts, or create an atmosphere of total objectivity through an illuminating homogeneity similar to natural light (Holl, Pallasmaa and Perez-Gomez, 2007; Duff, Kelly and Cuttle, 2017).

2.6 Roles and activities of the lighting designer

At the historical beginning of lighting design, the designer started from the generic need to illuminate sufficiently to arrive at creating the most suitable luminaire. Today, the availability on the market of luminaires for a vast number of applications brings a different approach to the development of the project: once the visual tasks have been established, the illuminance levels that are most suitable for enhancing the desired perceptive effect are selected, the most suitable luminaires and their spatial arrangement are determined, also in function of the constraints induced by the regulatory and architectural requirements. In this sense, the project represents one or more solutions, preferably optimal ones, according to the criteria established in the specifications. Often these requirements, depending on the project's complexity, need to be broken down into subsets that refer to parts of the project. This divide-and-conquer method is necessary due to the complexity of the project and the increasing number of technological and regulatory factors that influence design activity, such as the growing use of BIM methodology.

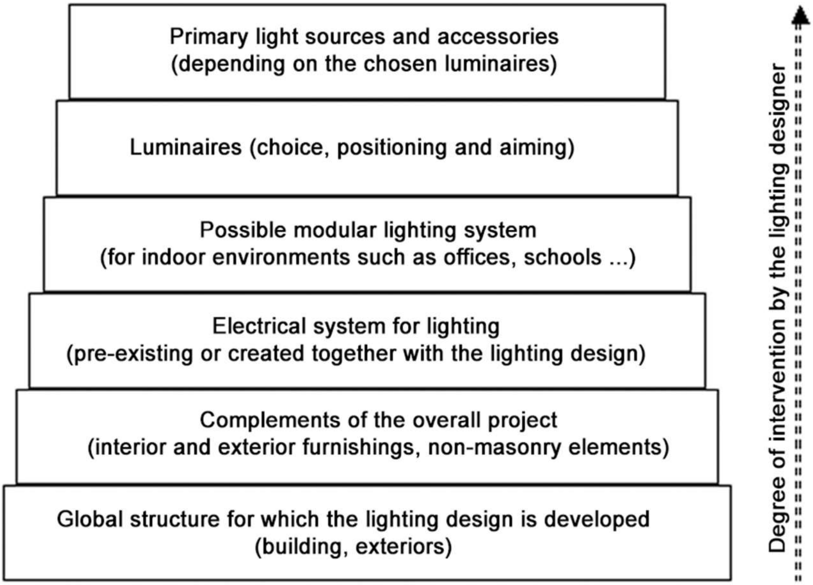

Figure 2.6 – Degrees of intervention by the designer in lighting intended as a subset of a global project.

Therefore, it can be seen that modern lighting design has many methodological aspects that we could imagine as harvesting design work. The project's first objective is to optimize the use of elements at various levels of design complexity. These include, in decreasing order by global application and increasing order by the amount of designer intervention and flexibility of use:

1. The structure, i.e., the lighting design, is a part of a building's renovation, redevelopment, or new construction project. Depending on the relationship established with the client, the lighting designer can also have a say at this macro level to optimize, where possible, the use of natural light or the harmonious integration of artificial lighting systems in a determined architectural context. Often the designer's intervention at this level does not occur, either because of organizational/communication constraints or because the lighting project is an autonomous activity applied to an existing structure that needs to be enhanced or whose lighting system is obsolete or non-standard.
2. The structure's interior and exterior furnishings. This level includes all the objects complementary to the civil design of the structure, such as movable surfaces, light-diffusing screens and curtains, skylight materials, plants, furniture, and everything that contributes to the definition of the architectural spaces and the distribution of lighting. At this level, the designer can also contribute to the building project by highlighting aspects related to the optimal use of light with respect to forms, arrangements, and visual tasks according to lighting regulations. It is helpful to note that at this level, there are many interests that the lighting designer shares with the interior designer, so much so that it is argued that for a complete technical and cultural education, both need to assimilate a mutual set of skills.
3. The electrical system. In some cases, for the enhancement and redevelopment of cultural sites or for aesthetic requirements, the electrical system can be designed by the lighting designer to fit harmoniously into the building project, respecting its aesthetics and at the same time fulfilling its task according to the power requirements by the luminaires. In other situations, the electrical system does not exist, or it is present but may need to be modified or adapted. With the advent of LED light sources, these often replace conventional light sources in a retrofit perspective without intervening on the electrical system.

4. The modular lighting system. In some cases, such as offices and work areas, the luminaries are organized in modules. The system's layout will then be completed by defining the lighting points. In a way, the system can be considered as a large integrated luminaire. In many cases, this is not used. At this level and the following ones, the lighting designer has a lot of autonomy within the design requirements.

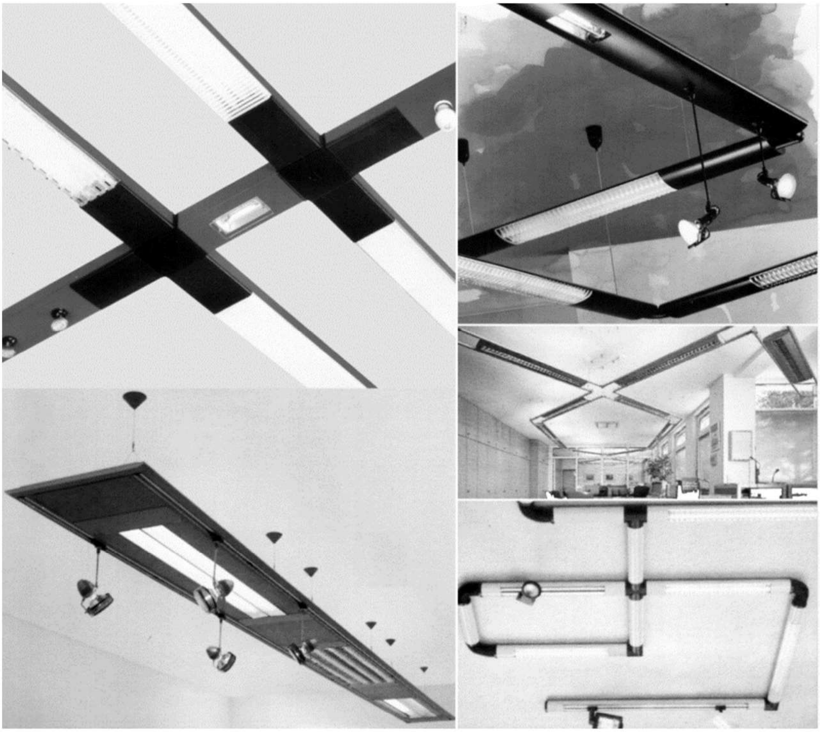

Figure 2.7 – Modular lighting systems. These devices provide support and electrical power to various types of luminaires which are thus integrated into an aesthetically homogeneous structure.

5. The luminaires. The luminaires' selection, arrangement, and orientation are the central stages of lighting design. The designer expresses his skills and creativity to meet the project's objectives within limits defined in the specifications. In many cases, the layout is constrained within the degrees of freedom represented by the structures of the

building project (Castiglioni, Baldacci and Biondo, 1991). The luminaires must comply with a criterion of aesthetically correct insertion while respecting the architecture of the space. From a photometric standpoint, the ideal position for a luminaire is often unsightly or impractical. The design of the luminaires themselves, when they cannot be concealed, must fit harmoniously into the architectural context to be lit. The designer must remember that the lighting system with accessories, cables, poles, and luminaires is visible even during the day under natural lighting and is therefore considered an interior or urban furnishing accessory that must fit harmoniously into a given architectural context with urban materials (Casciani and Rossi, 2017). In other cases, depending on particular applications, the lighting designer can also design one or more custom luminaires to solve specific lighting problems

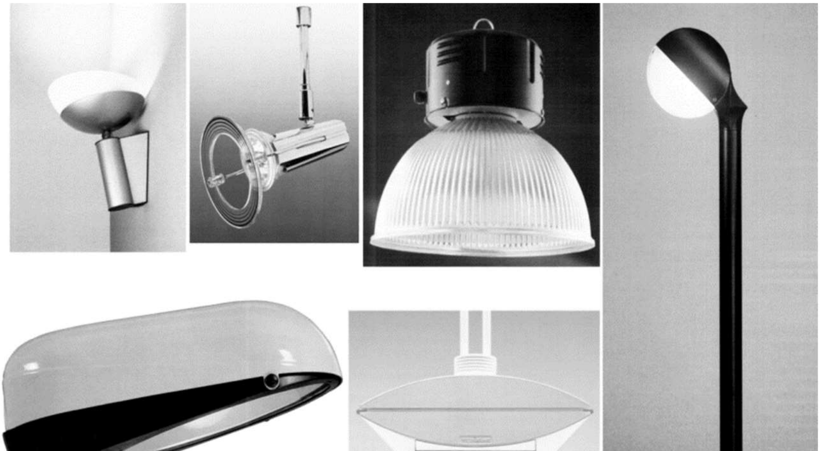

Figure 2.8 – Various types of luminaires for indoor and outdoor applications.

6. Primary light sources and accessories. The choice of which, within the degree of freedom allowed by the luminaires used and according to their arrangement and the amount of light required, provides the lighting designer with an additional degree of freedom to compensate for other design constraints connected with the building project. The luminaire and the integrated, non-replaceable lamp are increasingly becoming a single product with LED solutions.

Another fundamental objective of the design process is customer satisfaction. Several aspects can be highlighted regarding this objective. Unfortunately, at a higher level, customer satisfaction is highest when the lighting design in the building project envisages a minimal intervention and the costs are low. Going down in the level and generally in complexity and cost, in the influence on the building project, the lighting designer has vast degrees of freedom regarding customer satisfaction. Other aspects of customer satisfaction are related to achieving quantitative and qualitative lighting levels for people in the spaces envisaged by the project. While quantitative aspects are easily verifiable with practical measurements after the project's implementation, also in compliance with lighting regulations (CEN, 2021), qualitative factors are much more difficult to assess (Veitch, 2001). This is because they are subjective and depend on a reasonable degree of expertise concerning lighting culture, which is generally not widespread in the building design sector. And it is precisely on the qualitative and perceptual aspects that the function of the lighting designer is expressed in its differentiation from an electrical engineer or installer. This is where his training comes into play, making the lighting designer capable of managing both the technical-production aspects and the socio-cultural and aesthetic sides of lighting design (Aries, 2020).

In designing a lighting system, which is generally characterized by installations specific to the project, the harvesting approach has several advantages in relation to cost containment in the design and implementation phase. In fact, a from-scratch design of every single part of the lighting system is impractical in the hypothesis of a single implementation, which is almost a constant in this sector. Also, in the design of luminaires produced by lighting companies, the drafting approach is applied at a lower level to the various components of the product design, adopting economies of scale that make it possible to contain costs and times. This is possible thanks to the re-use of components and parts of the products previously developed by the manufacturer or third-party suppliers.

A reflection on the very nature of lighting design leads us to observe that its primary purpose is to manage, organize and optimize specific resources in the presence of assigned constraints. These constraints can be expected requirements, functionality, costs, laws, standards, and much more. But in some cases, constraints are not all set, and in this case, it is the designer who sets them. Generally speaking, constraints can be grouped into two categories: external constraints typically imposed by the client, regulations, and suppliers, and internal constraints self-imposed by the designer and which, in short, constitute a set of rules, including formal ones, that characterize the designer's operating methodology and may evolve over time as the designer matures professionally.

2.7 Innovation and methods

The lighting designer must therefore be able to understand and master a series of multidisciplinary, scientific-technological, psychological-perceptual, cultural, social, and even economic aspects, which make his task take on the characteristics of a product/service-system that is integrated into a set of correlated systems, rather than a single project-object isolated from its context (Sakao and Lindahl, 2009). It is also from this perspective that in the future, the lighting designer will have to increasingly integrate his work into the BIM methodology, even though there are no software tools yet to manage the technical aspects of lighting and color. The nature of illumination, strongly impregnated with technological contents in constant innovative evolution and influenced by the high number of relationships between the components that affect the final result, makes lighting design an activity characterized by the management of large quantities of information. This aspect is also influenced by a continuous revision of the steps involved in the design development methodology, which undoubtedly implies a burden on the lighting designer's permanent training and daily practice but are nevertheless facilitated by the use of new information and communication technologies. In some respects, the personal IT revolution since 1980 and the networked communication revolution in the 21st century have, as in many other sectors, influenced the development of innovation in lighting design.

Memory is sometimes short, and this is especially true in introducing new technologies that enter our daily routine. In fact, we can do a simple experiment to understand how much innovation permeates the majority of us; let's take a sheet of paper and try to remember and write down the years of our lives when we first started using the following tools: personal computer, CD-Audio, CD-Rom, MP3 player, mobile phone, Web, email, smartphone, and tablet. Next to the dates, let’s also try to write down the salient events in our lives during that period. On re-reading the list, we will be surprised to observe that, actually, many innovations have only become commonplace relatively recently, and we will wonder how we could conduct our professional activities and our daily lives without smartphones, PCs, and email. The answer is that our actions were still going on, but most probably less efficient. Many people view new technologies with reserve and suspicion, but they are not ultimately good or bad; our use of them allows us to evaluate them. The use of smartphones enables mobile communication that helps us plan our activities dynamically, according to the events of the day; it is fair to consider this a convenience that cuts unnecessary waiting periods and consequently allows us to have more free time. The same concept applies to the Web, which will enable us to do banking or postal operations without going to the bank or post office with the associated transfer and waiting times. Time is the most precious thing in our lives. Why waste it? A question remains: is the time we can save through the use of new technologies extra time for our leisure time or extra time for more work? The answer is up to each individual.

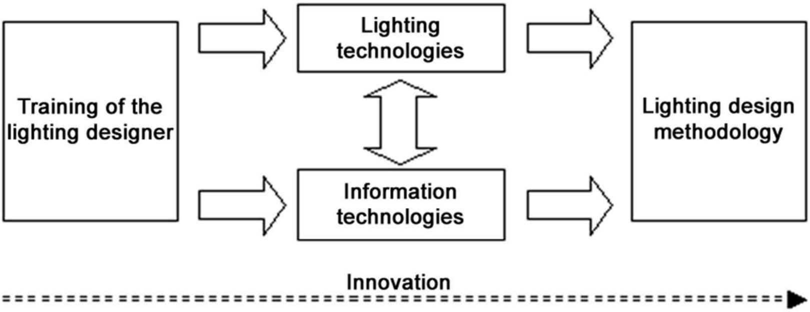

Figure 2.9 - Role of IT versus innovation in the training of lighting designers.

Over the years, a further push towards innovation in the lighting sector has also come from public innovation players, i.e., local, national, and international institutions. The institutions, less constrained than companies by the objective of immediate profit, have made a fundamental contribution to the development of innovation processes through public infrastructure development projects and the enactment of laws and regulations relating to the safety and functionality aspects of public and private lighting.

International organizations such as the CIE and national organizations such as CEI and UNI (in Italy) have experimented through working groups with methods and definitions of optimal lighting conditions for most visual functions of human activities, indoors or outdoors, whether in public places, such as museums, football pitches, and workplaces, or private ones, such as residential environments. The main parameters underlying these criteria include illuminance level, glare control through the UGR factor (CIE, 2010), and color rendering of light sources (CIE, 2017; IES, 2020) for visual comfort. The fruit of this research, also concerning the safety of lighting systems and luminaires, is now available in a series of up-to-date standards and recommendations, representing a set of constraints to be fulfilled to develop an organized and coordinated methodology for the process of lighting design (Boyce, 2019).

Indeed, innovation in industrial processes is certainly more weighted and linked to economic factors that have their assessment parameters: the containment of production costs, the efficiency of production processes, competitiveness on the market, and, ultimately, profit maximization. The lighting designer is often a freelancer, or a small design studio, for whom the use of new technologies and methodologies represents an investment in terms of training and updating. Whether these innovations are to be used in the installation or tools to support the design process is an expensive activity. On the one hand, therefore, technological innovation in lighting requires continuous efforts to keep abreast of available systems' state of the art. On the other, IT tools support the design process, which the designer must deal with in a way that is sometimes problematic, depending on his cultural, scientific, and technological background. It should be noted that, in lighting design, the use of IT tools to support project development and management involves a methodological change in the design process that has only recently taken place on a massive scale. Also, thinking to BIM, the reasons for this inertia in introducing IT systems lie precisely because their use involves a different approach to the design process and the objective difficulty of finding suitable software tools.

Today there are software, Lighting CADs, to support the work of the lighting designer; however, even the most advanced tools available are not magic boxes that accept input specifications to produce the output design. Actually, their use requires a wealth of technical skills in several disciplines, ranging from design, lighting technology, computer graphics, and visual perception, with expertise that often straddles the line between technological application and scientific research, with the aim of a correct interpretation of the results that can be produced. These tools enable a quantitative verification of the photometric quantities of the lighting design and digital images that are a support tool for the qualitative evaluation of light, which, however, must be read taking into account the limits of these tools in the reproduction of the visual perception of the lighting.

Over the last ten years, companies have gradually reduced the number of printed catalogs in favor of digital documents and websites dedicated to ever-changing product lists. The photometric characteristics of luminaires used in Lighting CADs can also be found and downloaded free on these sites. Other exciting aspects of support for the designer's work, provided by

IT, lie in managing helpful information flows concerning the harvesting connotation of the lighting project process. The technical data for luminaires are now increasingly accessible directly in the multi-brand electronic catalog, available in Lighting CAD tools.

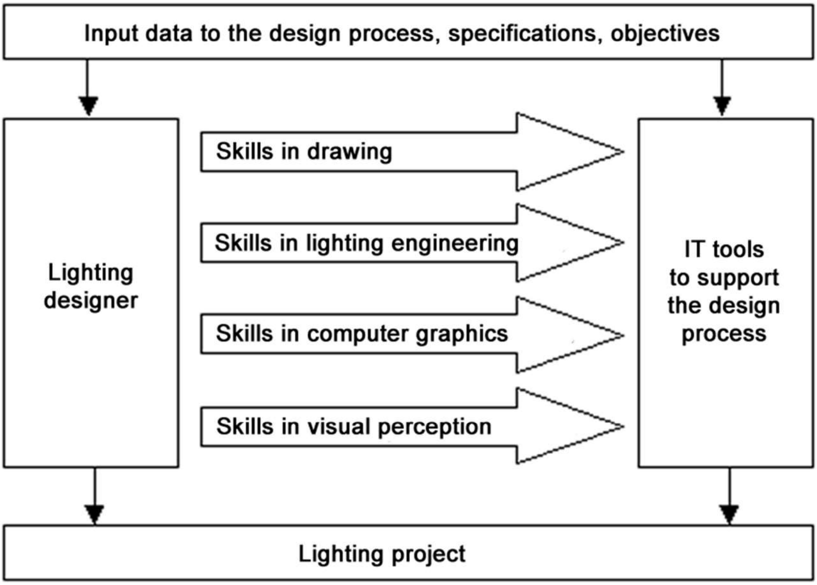

Figure 2.10 - Skills of the lighting designer with respect to software tools in the lighting design process.

The use of application programs also allows network communication to be managed. This facilitates the exchange and retrieval of information regarding the various levels of intervention of the designer in his relationship with the design team, the customer, and the companies supplying the devices that are the building blocks of the design harvesting activity. The Internet also provides valuable support in finding regulatory and legislative information by accessing the websites of entities promoting standards and recommendations and governmental organizations. Today, data on technological innovations presented by companies can be found on the Internet via web pages or by subscribing to specialized mailing lists that periodically send out bulletins on the state of scientific, technological, and regulatory experimentation in the lighting sector.

IT tools also enable a collaborative approach to project development at the network level. More and more today, the project has to be the result of a shared and integrated work of a team of people, both at lighting and building project level, developed by one or more project actors specialized in different areas of intervention and geographically distant, as is the case with the BIM methodology.

However, the most innovative aspect of the lighting design process essentially concerns the tools supporting the quantitative and qualitative assessment of light distribution in indoor and outdoor environments. Based on the computational and visual aspects of virtual reality, the PC workstation has become an indispensable tool for lighting calculations in the last ten years to the extent that it provides precise results concerning the requirements of national and international standards. Indeed, the old CIE calculation recommendations only provide for regular parallelepiped-shaped interiors but with limitations on the possible arrangements of luminaires (CIE, 1982).

In an area of constant technological change such as lighting, the use of IT systems in support of the project provides help in several areas:

1. Lighting calculations for the quantitative assessment of light distribution. The old CIE recommendations setting out the methodologies for calculating illuminance and luminance were presented between the 1970s and 1980s, at the dawn of the development of personal IT, and were used for a manual calculation. For this reason, and to simplify the calculation procedures as much as possible, they were developed based on numerous simplifying assumptions. While this has made it possible for years to carry out lighting calculations in the absence of a PC, this approach is only applicable to austere environments in which the presence of furniture or uneven distributions of light sources are not even considered. However, the gradual and steady increase in PC's power has made it possible to redefine and use more accurate calculation models borrowed from radiometry and computer graphics. With these new models, of which Radiosity (Goral *et al.*, 1984), Monte-Carlo Ray Tracing (Shirley, Wang and Zimmerman, 1996), and Photon-Mapping (Jensen, 1996) are the primary examples, the calculation of direct and indirect light distribution can be done much more accurately for environments of arbitrary complexity and for all kinds of luminaires. An upper limit to the possibilities of these new calculation models is typically only represented by the level of complexity of the geometric models, the number of light sources, and the parameters defined by the designer, which control the accuracy of the calculations.

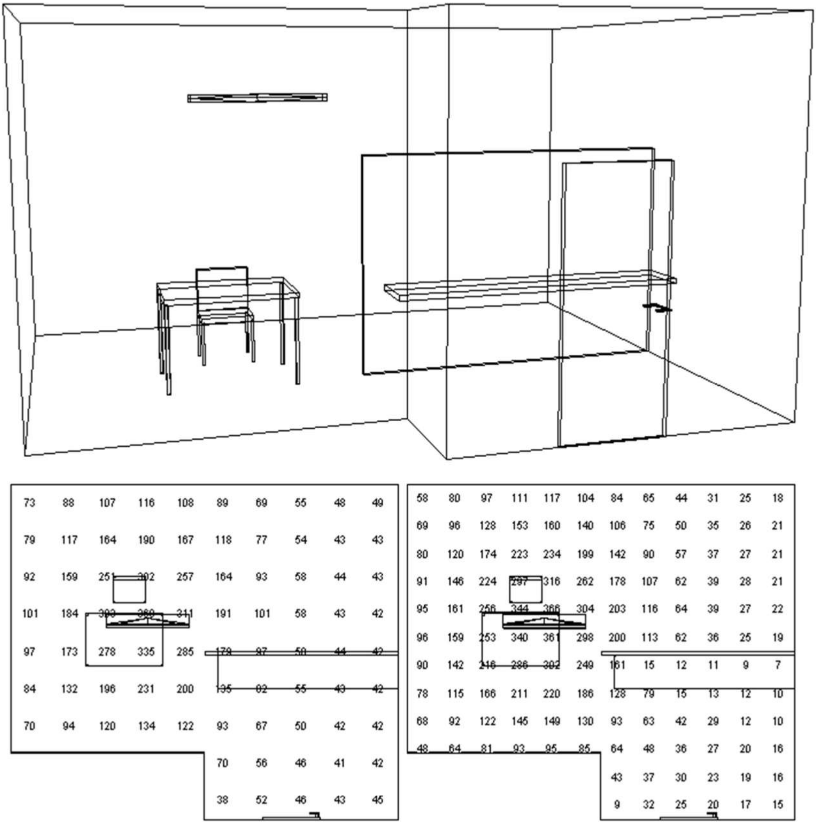

Figure 2.11 - Comparison between the illuminance levels (on the work-plane at the height of 85 cm), calculated with the CIE52 method (left) and radiosity (right). The elementary room model shown above has a lighting fixture equipped with two linear fluorescent lamps of 3350lm. The CIE calculation method ignores the shadows cast by the furniture elements and tends to overestimate the illuminance in the room's corners.

2. The creation of near-photorealistic digital images for the qualitative assessment of the lighting design and, more generally, a building project. In this case, we speak of virtual prototyping of the project, i.e., an approach aimed at creating prototypes using virtual reality and computer graphics techniques that can be used in all those cases where the physical prototypes are not feasible due to technological, visual-perceptive, or even budget constraints. The greater its visual perceptual

Figure 2.12 - Photorealistic rendering for the qualitative evaluation of light. Comparison between artificial and natural lighting vs only artificial lighting.

authenticity, compared to the reality it wants to represent, the greater the value of a virtual prototype. However, the value of a virtual prototype in the design process is even more significant as the expectation of the informational-visual capability required of it increases, and this is precisely the context of the qualitative evaluation of lighting design. In PC-supported lighting design practice, the virtual prototype is also completed through quantitative evaluation and analysis integrated with qualitative evaluation.

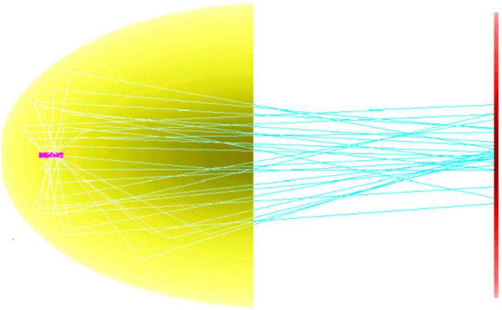

Figure 2.13 - Verification of the distribution of light rays in a reflector using CAD software for lighting product photometric test.

3. The verification of luminaires. Alongside tools to support the development of lighting design, software tools dedicated to testing reflectors and lenses for lighting product design have also come to the fore in the last 20 years. Using these tools, it is possible to simulate photometric calculations based on the characteristics of the bare lighting bodies and the materials and shapes of the reflectors and optics of the luminaire. This is an operation usually carried out in the laboratory using a goniophotometer and a working physical prototype of the luminaire at much higher costs. For this type of software, too, the working methodology is based on virtual prototypes, which do not represent complex environments as in the previous cases, but rather single luminaires. Their modeling is performed using the usual CAD/CAM software and then imported into the verification tool. The evaluation that can be carried out is generally quantitative and concerns the photometric and radiometric characteristics, leaving that of a qualitative nature to more traditional instruments. Alongside these, there are also tools for verifying thermal performance, which

enable the sizing of heat dissipation surfaces essential for the correct operation of LED sources.

4. The support of harvesting lighting design by network information tools, databases and workgroup tools. It should be noted that the availability and use of information systems are equally essential and complementary to the aspects discussed above. On the Internet, they provide access to regulatory, technological, and promotional information on tools and methods that can support the development of lighting projects. In cases where the project is produced by a workgroup, at the local level, workgroup tools provide valuable means for a collaborative approach by managing communications, project development versions, design process phases, and organizational-management aspects of the work. The future of the lighting designer will increasingly have to be integrated into the BIM methodology. If this has not yet happened, it is because there are no software tools available to support BIM in managing lighting and color calculations.
5. Visual communication in project presentation thanks to multimedia and integrated information management. Now that the development of information technology provides advanced support tools useful for the project's virtual prototyping, it is reductive to consider relying solely on paper-based project presentation tools. In addition, the software programs that can be used for design work often provide functionalities helpful in producing parts of multimedia presentations, such as digital video and three-dimensional models of environments or objects that can be navigated and explored interactively on the network (Web3D, 2020). A hypermedia presentation based on web technologies or digital video can be more easily created in this context. The fundamental media used in its composition are part of the computer-assisted lighting design process's intermediate and final products.
6. Management and control of lighting installations. The use of the LMS with management capabilities and interfaces to control large lighting systems has become widespread. The lighting can be switched on, off, and modulated according to various parameters to save energy and create special scenic effects with varying levels of illuminance and chromaticity. There are now apps for smartphones and tablets for residential and personal applications integrated into the IoT to control smart light sources. Innovation in this area is also moving toward lighting control for people's well-being (Rossi, 2019).

Networked information systems are constant throughout the design process. At the same time, the other types of IT tools seen above find their place with different degrees of use in the various phases of the project development process. Hypermedia visual communication tools supporting the presentation of the project to the customer intervene almost exclusively in the final stage of the project, except for their use for presentation or evaluation of limited parts in earlier phases. While LMSs are used for commissioning and managing the lighting system when it is fully operational and for monitoring and maintaining the system.

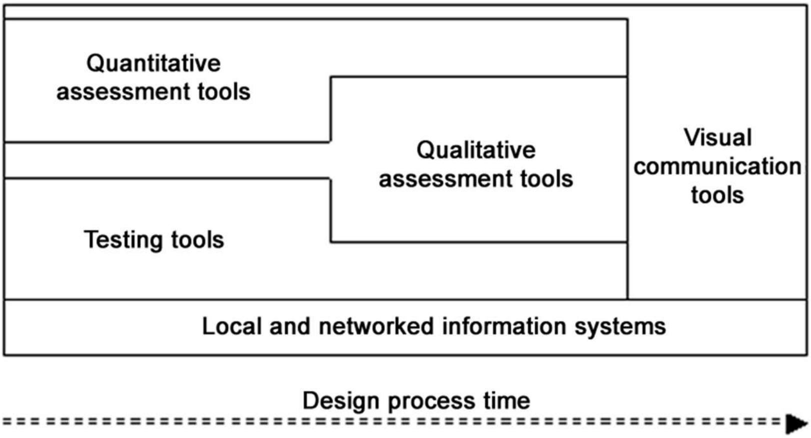

Figure 2.14 - Degree of use of IT tools in the project development time.

In the initial phase of the design process, using Lighting CAD for the quantitative evaluation of the project and for the verification of equipment is predominant. In this phase, the lighting designer has to face the photometric constraints and problems without forgoing, however, the first tool supports the qualitative idea evaluation. In fact, these make it possible to observe at an early stage if the project's technical constraints do not distort the project's poetic and artistic ideas. As the design process progresses, this relationship is reversed, with a more decisive intervention in the qualitative aspects and reserving the quantitative elements to check the constraints: the photometric requirements. Such a situation is influenced by lighting design's highly technical and scientific nature. It is worth remembering that what is being evaluated here is the degree of use of the IT tools. At the same time, development in the designer's mind proceeds in an integrated form based on the information provided by the available tools. In design before the advent of IT, the two roles of quantitative vs. qualitative, in using tools in the design phase, were sometimes reversed. In the past, the limited number of modeling tools available did not allow for a systematic and integrated approach as made available by today's design support tools.

2.8 Conflict of interest declaration

The author declares that nothing has affected his objectivity or independence in the production of this chapter. Neither the author nor his immediate family member has any financial interest in the people, manufacturer or topics involved in this article. The author also declares that no conflict of interest, including financial, personal, or other relationship with other people and organizations, could inappropriately influence, or be perceived to influence, this work.

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Chapter 3
Perception of Light and Color

Maurizio Rossi – Politecnico di Milano

Abstract

As illustrated in the previous chapters, Lighting Design is not a mere matter of exclusive engineering compliance with international lighting standards. Cultural aspects move the lighting designer between the artistic experience, the project development methodology, the new technologies, and, equally important, the visual perception that humans have of light and color. This topic will be explored in this chapter, from the perceived effects of the real world to the virtual one of rendering.

Keywords

Light, lighting, color, visual perception

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3.1 Introduction

Light is the basis of life on our planet. Without sunlight, with the alternating sunrises and sunsets, there would be no life on Earth. Light is also energy. The lives of human beings are directly or indirectly influenced by sunlight (Begemann, van den Beld and Tenner, 1997; Gochenour and Andersen, 2009). Without the Sun, all the most modern human technologies would still not be able to guarantee the survival of our species, plants would die as well as phytoplankton production (Field *et al.*, 1998), and thus the oxygen production and the food chain for all living things would be interrupted.

The wave-particle model of light photons was defined with quantum physics, essential for the treatment of atomic processes. However, the idea of designing lighting using quantum physics methods is unrealistic and pointless. For all that concerns lighting design, light is considered electromagnetic radiation, and its study falls within the scope of radiometry and photometry. This simplification concerning photon theory does not entail any loss of precision in practical terms, for several reasons that can be summarised as follows:

- In everyday applications, objects stand still or move at speeds several orders of magnitude slower than the speed of light.
- The size of these objects is much greater than the wavelength of light.
- The mass of the objects is much lower than that of the Sun or black holes that can deflect light from its straight path.
- The photoelectric effect produced on metallic objects is of no interest to lighting management purposes.
- The physical behavior of the ideal black body is of limited interest only for producing artificial light by heating Tungsten. This phenomenon is used for the production of old classic incandescent light bulbs.

Even under the assumption of considering light as electromagnetic radiation, handling the calculations to describe its behavior is still highly complex. Indeed, although vector differential equations describe the behavior of the electromagnetic field (Maxwell, 1864), they are challenging to solve in practice for applications that deviate from some ideal cases of physics. In particular, two aspects complicate the description and simulation of the behavior of light even if the PC is used for solving the calculations. Light is described as a set of electromagnetic waves of wavelengths between 380 and 780nm, so each ray of light would have to be defined by a spectral vector function. In addition, the interaction of light with objects should be described mathematically in terms of geometric and micro-geometric elements as well as physical and chemical aspects. This information is difficult to manage and rarely found in lighting design practice.

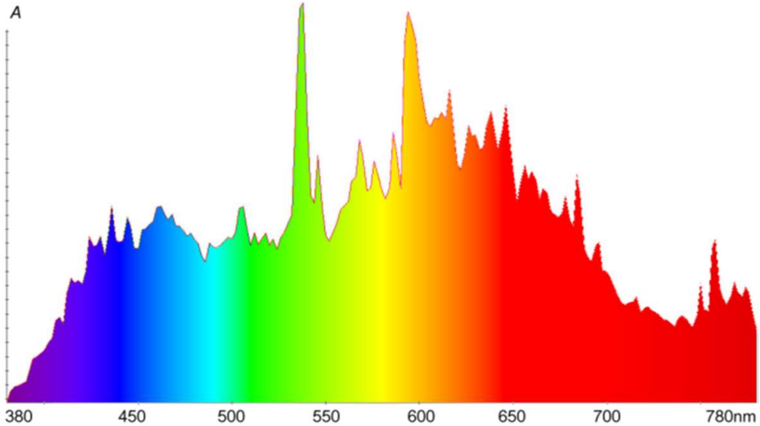

Figure 3.1 – Example of a representation of the spectrum of a beam of light. The spectral power distribution (SPD) indicates the contribution of monochromatic components at various wavelengths within the visible spectrum between 380 and 780nm.

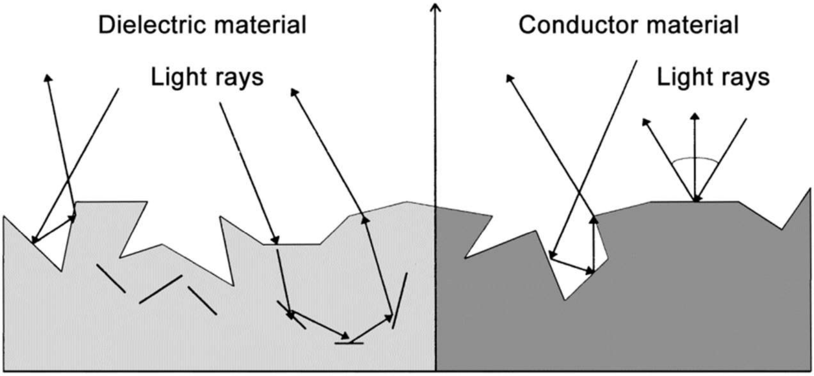

Figure 3.2 - When calculating the interaction between light and matter, it is impossible to give an exact geometric description of the surface's actual micro-roughness that contributes to the visual appearance of materials.

For these and other reasons, simplifying assumptions are made about the nature of materials and light, which on the one hand allow practical problems to be solved, but on the other introduce a considerable margin of error into the results that can be obtained. So that they cannot be considered valid from the standpoint of physical correctness but are helpful for the analysis of lighting design parameters.

In general, an intuitive rule applies, which can be stated as follows: the more simplified a calculation concerning the description of light is, the greater the error in the results. In this sense, using a PC instead of manual calculation methods already represents a major step forward in evaluating the quantitative aspects of lighting. On the other hand, concerning the aesthetic and qualitative factors, the PC, although indispensable, makes it possible to obtain good results, which do not have absolute validity but must be interpreted. This is due to a series of phenomena linked to the human visual (HVS) perception that we will see in this chapter.

3.2 Vision: facts and illusions

Perceiving the world around us is not just a simple collection of sensory data (Gibson, 1966). Through our senses, and in this particular context, our vision, we are able to create a mental representation of the world around us. Vision is the primary human sensory system (Gregory, 2015). Our visual system has evolved in such a way as to best interpret the informative richness of images (Land, 1977), thus developing sensitivity and adaptation characteristics that are interesting to analyze.

Vision is a process that begins in the eyes and is completed in the cerebral cortex. Rather than a separate, autonomous sensor that transmits data to the brain for further processing, the eyes can be understood as a part of the nervous system, working with the cerebral cortex to adapt and process visual information (Conway, 2002).

The cerebral cortex does not receive a faithful copy of the stimulus received from the outside world but largely unknown processing of the original optical information.

Each stage operates on particular stimulus characteristics, such as color, shape, movement, and depth, activating under certain conditions to process the signals it receives (Zeki, 1993). Therefore, there is no specific area of the brain interpreting what we see. Still, visual processing takes place simultaneously in several different regions of the cerebral cortex located in the occipital region. It is, therefore, more appropriate to speak of a perception process. Let us now look at some of the characteristics of this process, starting with the structure of its first component, the eye.

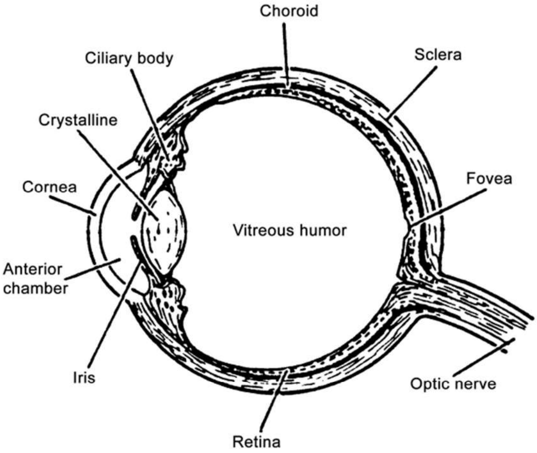

Figure 3.3 - Representation of the eye.

The eye is formed by the eyeball, which is located in the orbital cavity of the skull. It can be considered a small camera: the eyeball wall is covered on the outside by a robust white membrane called the sclera. This membrane becomes transparent and more curved on the front, forming the cornea. Immediately below the sclerotic membrane is the choroid membrane, which anteriorly has an opening, the pupil, with an adjustable diaphragm, the iris, which has the same functions like the diaphragm of a photo camera. Behind the pupil, the opening is the crystalline lens, a biconvex lens-shaped body made up of transparent cells that, by deforming through the ciliary muscles, allow the image to be focused on the retina.

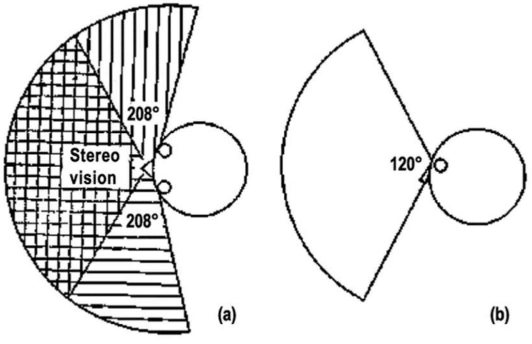

Figure 3.4 - Horizontal (a) and vertical (b) human field of vision.

Congenital problems with the shape of the eyeball or crystalline lens result in the classic visual defects of myopia (excessively elongated eyeball), hypermetropia (excessively shortened eyeball) and astigmatism (asymmetrical crystalline lens). Age-related degeneration also reduces the ability of the crystalline lens to change shape to adapt the focus, causing presbyopia. It is interesting to note that the lateral visual field of the two eyes is about 208° and the vertical one about 120°, as is the angle of both eyes in stereoscopic vision, which helps i depth perception.

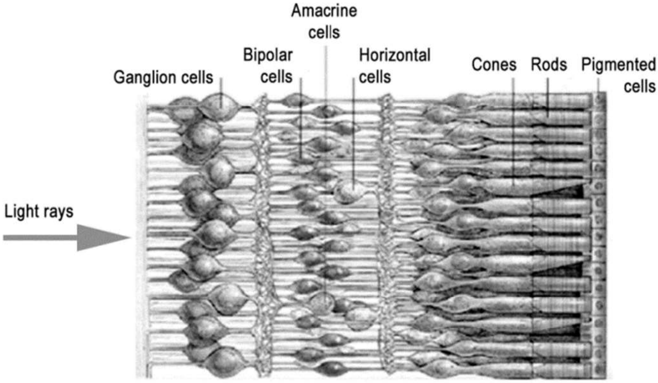

Figure 3.5 - Structure of photosensitive and neural cells in the retina.

The innermost layer of the eyeball is the retina, which contains nerve cells of various types, including light-sensitive receptors, cones, and rods. The cones react to high light stimuli mainly in daytime vision (Photopic), while the rods are also active in low light conditions typical of night vision (Scotopic). Cones and rods, stimulated by light, generate electrical signals through biochemical processes. These impulses pass, also in the retina, through a series of specialized nerve cells: the amacrine, ganglion, bipolar and horizontal cells, which then convey them to the optic nerve and, through the latter, to the cerebral cortex.

There are three types of cones sensitive to different wavelengths. Each cone type has its own spectral sensitivity for varying wavelengths. The combination of the three different sensitivities guarantees coverage of a light spectrum in the range 380-780nm, the so-called visible spectrum. Having three different signals available, depending on the frequency of the light received, enables the perception of color, as we will see in detail later. In contrast, the rods are all of the same type and only perceive light levels in colorless vision.

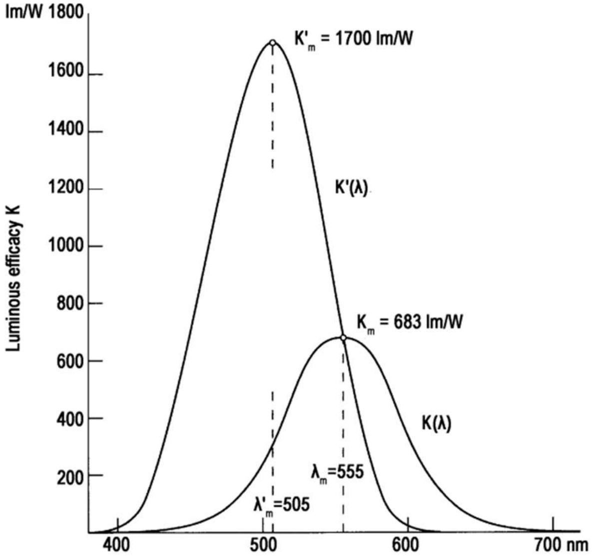

Figure 3.6 - The photopic K(λ) and scotopic K'(λ) spectral luminous efficacy curves define humans' photopic and scotopic visual sensitivity to electromagnetic radiation.

Another critical aspect is that humans are sensitive to radiation in the electromagnetic spectrum according to wavelength. Outside the range 380-780nm, the visible light, we do not perceive anything, which is why we are unable to see infrared (IR) and ultraviolet (UV) radiation. Within the light spectrum, we are more sensitive to the frequencies that produce the stimulus of green and yellow than those producing blue and red. This effect was described by the CIE in 1924 with the definition of the photopic luminous efficacy K(λ) of the standard observer, determined as an experimental mean value on some human subjects, which defines the basis of photometry and colorimetry (CIE, 2018).

Photometry is the science of describing the human visual perception of electromagnetic waves, that is, light. Considering light as electromagnetic radiation allows us to study it within the framework of radiometry, while photometry tells us how this radiation is perceived. Each spectral, radiometric quantity can be associated with the analogous photometric quantity, e.g. the radiance $L_e(\lambda)$ corresponds to the luminance L_v.

K(λ) is, therefore, the basis for the definition of all photometric quantities, based on the perception of electromagnetic waves, which are in turn described by radiometric quantities. The main ones are:

- Luminous flux. Obtained from the radiant flux. Describes the amount of light energy that flows in one second and describes how much light comes out of a light source. It is measured in lumens [lm].
- Luminous intensity. Obtained from the radiant intensity. Describes how the flux varies with respect to the angular direction in which the light exits a source. It is measured in candelas [cd]. The set of values of the luminous intensities in the space around a light source defines its photometric solid.
- Illuminance. Obtained from irradiance Describes the amount of flux arriving over an area of one square meter and is used to describe how much light gets on a surface. It is measured in lux [lx]
- Luminance. Obtained from radiance. Describes the amount of flux from a surface, visible through a certain solid angle, and is used to describe the sensation of brightness perceived by the human eye or a generic sensor. It is measured in candelas on square meters [cd/m^2].

K(λ) is only valid for photopic vision, i.e., for perceived average luminance levels above 3cd/m^2, i.e., in the case of daytime vision. If the average perceived luminance is less than 0.001cd/m^2 , this is called scotopic vision K'(λ), which can be seen at night under a starry sky. For intermediate luminance values, we have mesopic vision.

The scotopic spectral luminous efficacy curve differs from the photopic curve in two respects. The maximum value $K'_{max=}$1700 lm/W is much higher than the maximum photopic sensitivity K_{max}= 683 lm/W. This means that we have, on average, a two and a half times higher sensitivity to light radiation for low luminance levels. Maximum photopic sensitivity occurs for the 555nm wavelength, which corresponds to the yellow zone, while scotopic sensitivity occurs for 507nm, which shifts towards the green area of the spectrum. This means that we are more sensitive to colors tending to yellow for high luminance levels, while for low luminance levels, we are more sensitive to green. This difference can be easily observed by normalizing the effectiveness to obtain the corresponding efficiency curves:

$$V(\lambda) = \frac{K(\lambda)}{683\ \mathrm{lmW^{-1}}} \qquad V'(\lambda) = \frac{K'(\lambda)}{1700\ \mathrm{lmW^{-1}}}$$

The arrangement of photosensitive cells on the retina is not uniform. There are about six million cones, and they are concentrated in the central area of the retina, the fovea, which corresponds to the optical center of the eye. There are about one hundred and twenty million rods in the peripheral regions. The distribution of cones and rods is therefore inversely proportional. There are more cones and fewer rods in the center of the retina, while at the periphery of the retina, the proportion is reversed (Bertelli, 2019).

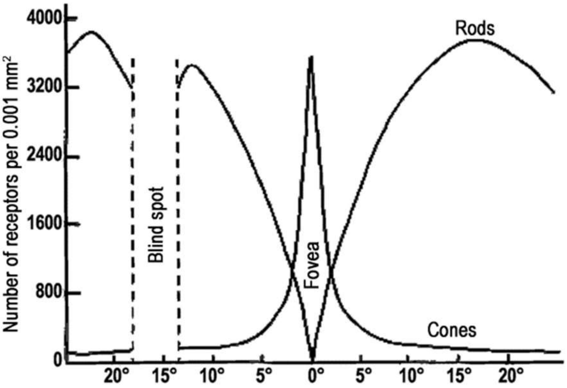

Figure 3.7 - The distribution of photoreceptors with respect to the visual angle centered on the fovea.

The fact that most of the cones reside in the central part has the consequence that human vision is active. To observe something well, we have to look for it with our eyes. An image or film is not viewed passively but actively observed. On an image, the gaze travels along paths to collect visual information. These paths mainly follow the edge areas and, in any case, areas with high visual information content.

This scanning mechanism also serves to refresh the contrast of an image. This is because, to perceive detail through contrast, it is necessary to look through the fovea, where there is the greatest density of cones responsible for the spatial resolution capacity of our visual system. Contrast Sensitivity Function (CSF) describes the contrast sensitivity of the HSV as the observed spatial frequency varies, i.e., when the linear size of the image details changes (Tatler *et al.*, 2010).

The minimum perceivable contrast values are related to a given level of brightness, so it must be taken into account that the contrast sensitivity characteristics vary with the general brightness of the scene. In addition, near transition zones, there is often an effect known as Mach band that, in order to highlight the contrast between different zones, makes us perceive a greater difference in brightness levels than the actual one (Mach, 1959; Ratliff, 1965).

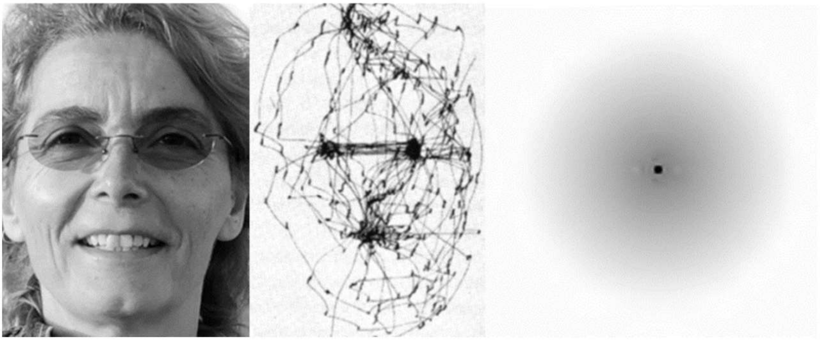

Figure 3.8 - Left and center: the observation paths of the eye focus on the areas of variation of contrasts to perceive the image. The image on the right represents a shaded disc. If you fix your eyes perfectly still for a few seconds on the central black dot, the circular shape tends to disappear due to the loss of contrast and eyes movements.

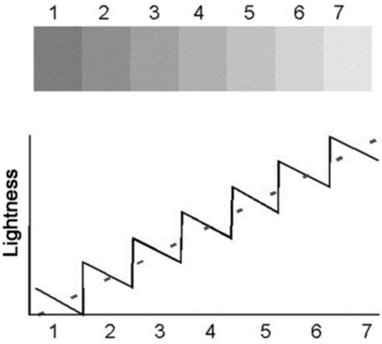

Figure 3.9 - Mach bands. At the top, there is a regular greyscale of uniform color. The diagram below illustrates the illusion of varying perceived lightness: near the left edge, each tile appears lighter and at the right edge darker. The overall perception is that each tile is not uniform but degrades from left to right.

The cause of this effect lies in the joint action, called action-inhibition, of the receptive fields of the visual system. A receptive field is a visual field region that collects a set of interacting photoreceptors. The action-inhibition mechanism, called center-periphery, occurs in two ways: center-excited/periphery-inhibited or center-inhibited/periphery-excited and enhances the response in transition regions, i.e., where the image changes from one luminance level to a different one. The perceptual consequence is an enhancement of contrasts. Another example of this phenomenon is Hermann's optical illusion, which presents a regular grid of dark squares on a light background. At the intersection of the white stripes between the black squares, the action-inhibition mechanism makes us perceive grey areas that do not exist (Hermann, 1870; Schrauf, Lingelbach and Wist, 1997).

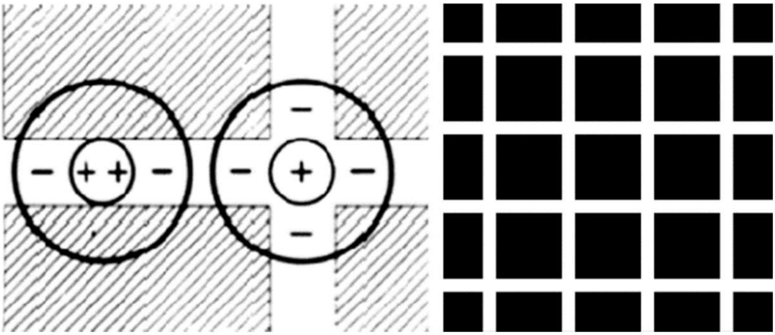

Figure 3.10 - Hermann's optical illusion: demonstration of the action-inhibition mechanism of receptive fields.

Like that of the Mach bands, this effect is explained by the diagram in the figure, in which two zones are taken as examples. The circles indicate two receptive fields; in the left field, the amount of light signal (white areas) falling in the inhibition region (marked with the minus sign, the circular crown) is compensated by the dark areas falling in the same region. The opposite is true in the right field, where the extensive light areas in the inhibition region contrast with the activation signal in the central region, creating the sensation of a non-existent dark area.

Each receptive field is therefore composed of a certain number of photosensitive cells, but this number varies depending on the position on the retina. Particularly in the central part of the retina, the fovea, receptive fields are made up of a minimal number of cells, making it possible to distinguish small details of images. In contrast, in the rest of the retina, the receptive fields are made up of a much larger number of photoreceptors and are therefore unable to distinguish image details.

We can demonstrate this physiological structure of the retina with a simple experiment: we try to fix our gaze on a word of this text and, without moving our eyes from that word, we try to read the adjacent words. We notice that as the distance increases, the words become more and more confused and indistinguishable.

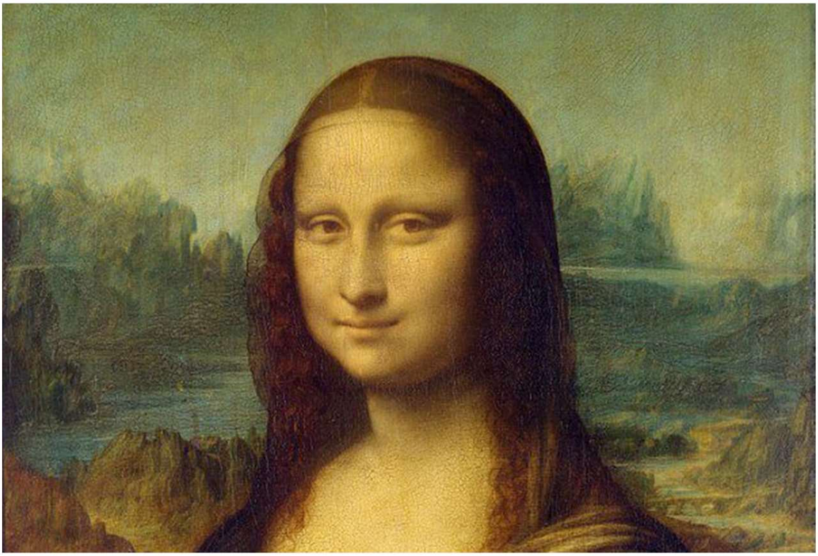

Figure 3.11 - The changing smile of Leonardo's Mona Lisa.

But this organization of receptive fields is also said to be at the basis of one of the most famous optical illusions: the smile on Leonardo's Mona Lisa, which appears and disappears depending on how one looks at the painting (Livingstone, 2000). If we look directly at the lips of the Mona Lisa, we notice that the smile is very thin, almost absent. However, if we look at her eyes, her smile changes and appears much wider. This is because by staring into the eyes, the mouth falls into the periphery of the field of vision, and we are no longer able to distinguish the detail of the mouth but only the shading at its sides, which makes her smile appear much larger.

3.3 Perceptual adaptation of vision

Returning to the examination of the structure of the retina, it is interesting to note that light does not directly hit the cones and rods directed towards the brain but is also reflected from the bottom of the retina. The light passes through layers of blood-rich tissue during this journey, but we do not see a red or pink world. The reason lies in the multiple adaptation mechanisms of our visual system, which we will analyze in detail later. This orientation of the photoreceptors imposes a particular configuration: the bundle of cells' axons, which must reach the cerebral cortex, gathers towards the center of the eye in the optical nerve and exits the eyeball at an area known as the blind spot. Our retina has no photoreceptors in this area, but despite this, we do not have the sensation of having areas of the visual field without a signal. The brain completes the missing visual field in the blind spot.

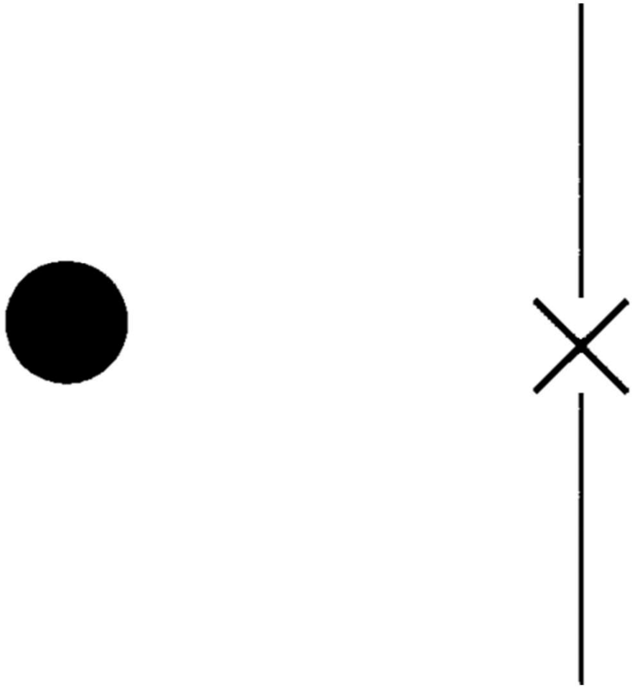

Figure 3.12 – Simple experiment confirming the existence of the blind spot.

To verify this phenomenon, simply perform the following experiment. Covering your left eye, fix the dot in the left of the figure, then move the book in front of you, still using one eye and, keeping your attention on the cross, look for the distance (around 20cm) where the cross will disappear. It disappears because you have found the correct distance so that the cross's projection on your retina is exactly on the blind spot. The brain reconstructs what is missing in the blind spot, with the background or using what is around it. In this case, a continuous vertical line is perceived

Adaptation mechanisms provoke phenomena identified with the name of perceptual constancy, thanks to which a scene is perceived in the same way even when lighting conditions change within fairly wide limits. The perceptual constancy, related to brightness, lightness, and color, allows us to see the world stably under the most diverse observation conditions (Land, 1977).

All this points to a discrepancy between the physical visual information we receive about the world around us and how we perceive it (Hering, 1964). In other words, the HVS is undoubtedly an effective tool for extracting visual information, but since it adapts to the environment, it is certainly not a measuring instrument.

Lightness constancy adapts the visual system to variations in lighting, which in natural scenarios can vary by more than six orders of magnitude, from a sunny day to the darkness of a forest. In each context, our visual system tries to produce a similar stimulus after an adaptation phase, and the adaptation time varies according to luminosity (MacEvoy and Paradiso, 2001).

Figure 3.13 – Simultaneous contrast. The small central square, identical in all four cases, is perceived as lighter or darker depending on the grey surrounding it. The lighter the background color, the darker the center appears, and vice versa.

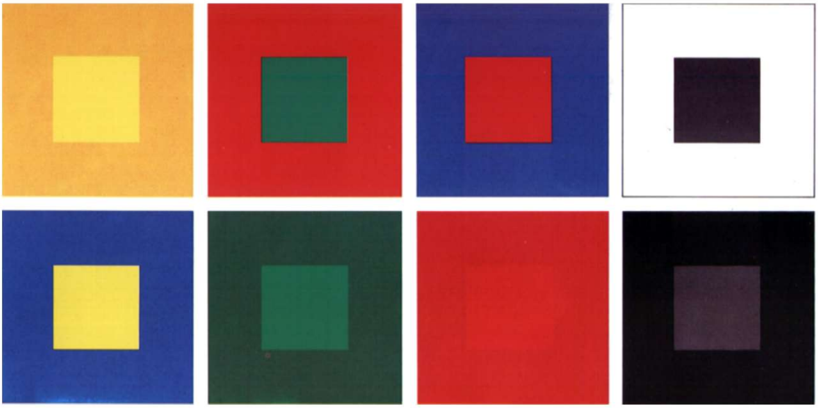

Figure 3.14 - Simultaneity contrast with colored figures.

Therefore, the feeling of the lightness of a surface is not a measure of the amount of light reflected directly from it but is somewhat linked to the relationship of this lightness to its surroundings. This principle of adaptation is at the basis of a classical optical illusion, called simultaneous contrast, which makes us perceive the same surface with different levels of brightness as the background changes.
Color constancy is the ability of the human visual system to compensate for apparent changes in the color of objects due to spectral variations in the light source (Monge, 1789). The signal that reaches our visual system results from the interaction between the light that illuminates the object and its reflective properties. Consequently, a white sheet illuminated by a red light and a red sheet illuminated by a white light reflect similar light spectra. In reality, thanks to the phenomenon of color constancy, our visual system can adapt to a possible chromatic dominance, due to the light source and attenuate it considerably. To understand the effects of this adaptation, we can look at the figure, in which we see four photographs of a shot taken under four different illuminants. In the picture, which captures physical reality, it is possible to see how the dominant colors due to lighting alter the colors in the frame. The same experiment, observed in person, would allow us to see the different colors better, as our visual system attenuates the dominant colors due to lighting.

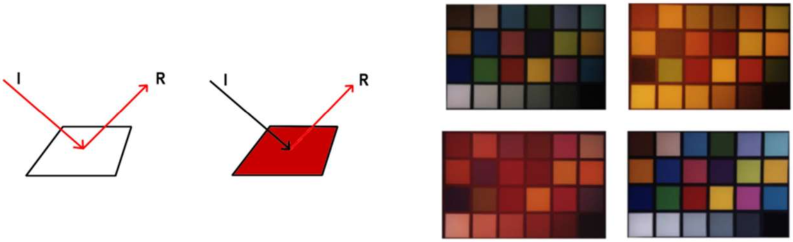

Figure 3.15 - Left: colored reflection. Right: Variation of illuminants on the same surface, in clockwise order from the top, left fluorescent lamp, incandescent lamp, sunlight filtered by clouds, incandescent lamp with a red filter.

This experience is familiar to anyone who has taken photographs in artificially lit environments using sunlight settings. The photograph takes on a strong yellow-orange dominance with incandescent lamps, while a strong green-blue dominance can emerge with fluorescent lights. However, when we look at the scene, the dominant is not perceptible, not because it is not present, but because the visual system adapts by eliminating it.

3.4 Color

At the beginning of the 20th century, with the spread of lithographic printing in visual communication and the production of colored paints, the problem of describing color unambiguously arose. Until then, for centuries, the model used was the artistic model of painters. In this model, the primary colors arranged in a circle were desaturated by adding white in the center of the palette. Lightness obviously depended on the amount of light reflecting off-color and was partly modulated by adding black. In this artistic model, color is defined by the three parameters of hue, saturation, and lightness. Based on the observation of the characteristics of the human visual system, the researchers then attempted to describe color in an unambiguous numerical way using hue, saturation, and lightness values,
The rods have a higher absolute sensitivity to light radiation, are responsible for the scotopic vision for low levels of illumination, and produce colorless vision based only on differences in lightness. The sensation of color is only perceptible with sufficient illumination levels in photopic vision. It results from the fact that there are three different types of cones, each characterized by pigments with different spectral absorption curves.

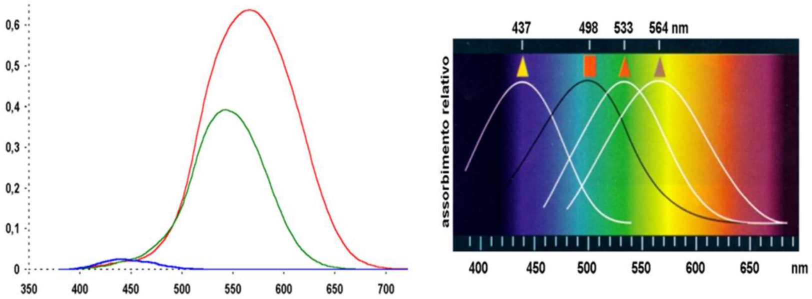

Figure 3.16 - Absorption of cones, absolute (left), and normalized value (right).

The first type of cone, L, has a sensitivity range in the longer wavelengths, with a maximum of 564nm, in the red zone. The second type of cone, M, has a range of sensitivity that is more shifted to the middle region of the spectrum, with a maximum of 533 nm, in the green-yellow zone. Finally, the third type of cone, S, is sensitive to the short wavelength region, with a maximum sensitivity of 437 nm, in the blue zone.
The fact that the sensitivity of S-cones is much lower does not mean that they are less sensitive to light, but rather that the number of S-cones is only about 10% of the total.

The different sensitivities and quantities of cones result in different wavelength discrimination abilities. To measure it, experiments of color matching have been carried out (Wright, 1929; Guild, 1931). A circle is divided into two halves; on one half, monochromatic light of known wavelength is projected; on the other half, three monochromatic red, green, and blue lights are projected, varying the amount until the observer begins to perceive the same color in the two halves of the circle.

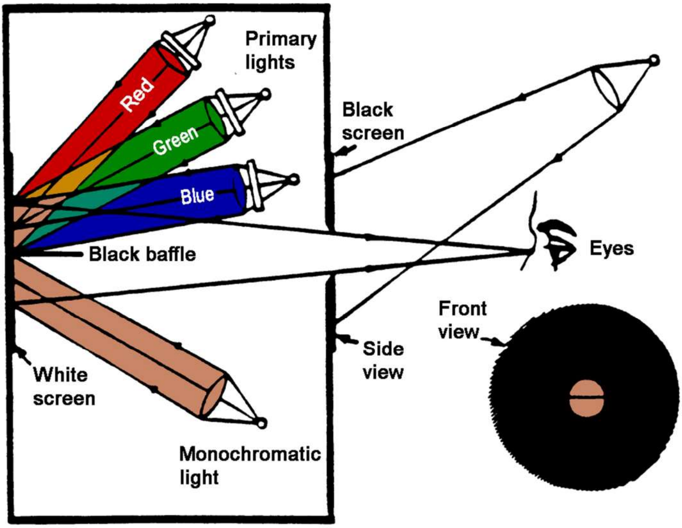

Figure 3.17 - The color-matching experiment by Wright and Guild in the 1920s demonstrates the tristimulus theory. The choice of the wavelength of the three monochromatic primary sources is critical in the experiment. These must be linearly independent, i.e., none of the three must be reproducible by modulating the other two.

The role of the three types of cones in forming the color signal was first identified by von Helmholtz. Through experiments carried out in the mid-19th century, he demonstrated the ability of cones to react to light stimuli of different wavelengths (Helmholtz, 1867). As a result of these studies, several models of color perception have been formulated, the main one being the Tristimulus model. The tristimulus model lends itself to mathematical processing and accurate quantitative representation of the color. To understand this, we can start with the description of the experiments by David Wright and John Guild. In these experiments, a person observed an area divided in two. In one half of the visual field, a sample of monochromatic light of known wavelength was projected, and in the other half, three monochromatic lights of varying intensity were projected. By adjusting the powers of these three colored lights, the observer had to try to reproduce a color that looked the same as projected in the other half of the visual field. The result of these experiments, which seems obvious today, was surprising at the time. By mixing just three colors, it was possible to obtain nearly all the monochromatic colors of the visible spectrum. Indeed, for some particular wavelengths, even modulating the three primary sources in all possible ways, an equivalent perception could not be achieved. However, perceptual equivalence could be attained by adding small amounts of one of the three primaries to the sample source. In the graph resulting from the experiment, this means that one of the three primary lights is shown with a negative value for some wavelengths, which would not make sense from a physical standpoint.

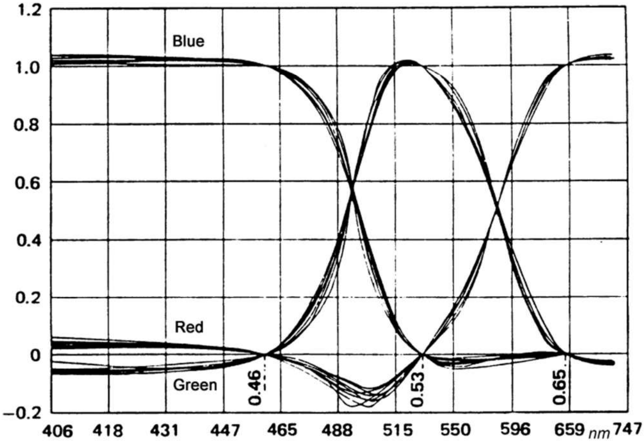

Figure 3.18 - Results of Wright's experiment conducted on various human observers. The ordinates show the tuning level of the three primary monochromatic sources, which were chosen by Wright at wavelengths of 460 nm for blue, 530 nm for green, and 630 nm for red.

Light radiation is absorbed in different percentages by the photopigments in the three types of cones and stimulates them in different ways. Along the visible wavelength spectrum, each group of photoreceptors of the same kind receives electromagnetic radiation according to its sensitivity and adds it to the other types of photoreceptors. The colors of the lights we see are thus associated with the different percentages of stimulation of the three types of cones, which explains why many different color nuances can be perceived with only three types of receptors. In this way, any spectral distribution of light energy is summarised in three values, known as tristimulus, and each perceived color results from a particular triplet. However, since the basic operation of perception is an integration in the frequency domain of the spectrum, this entails a loss of information. It may happen that different spectral energy distributions give rise to the same tristimulus. In these cases, known as metamerism, the perceived color is the same for a diverse light spectrum (Wyszecki and Stiles, 2000).

Considering that the spectral distribution that hits the eye is the result of the interaction between illumination and spectral reflectance at the observed point, it can happen that under some illuminants, two objects with different reflectance generate the same tristimulus values, i.e., they are metamers, while they would not be under other illuminants. For example, two fabrics may appear to have the same color under the artificial lighting of a retail store while appearing different when viewed under sunlight.

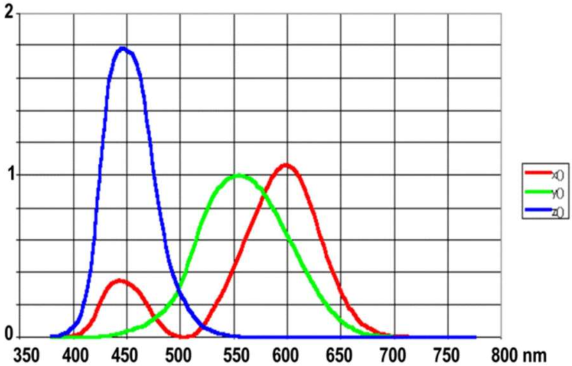

Figure 3.19 - The spectral color sensitivity curves of the CIE standard observer defined in 1931.

3.5 Color spaces

Based on the experiments of Wright and Guild, the CIE defined the average color perception characteristics of humans in 1931 by defining the three sensitivity curves of the standard observer (ISO/CIE, 2019):

$$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$$

These are different from those measured experimentally. For reasons of mathematical convenience, these were obtained by transforming the original Wright and Guild curves to eliminate the negative sensitivity values that do not make sense from a physical standpoint, imposing that:

$$\bar{y}(\lambda) = K(\lambda)$$

and making sure that the area under the three curves was equal for reasons of energy balance (CIE, 2018).

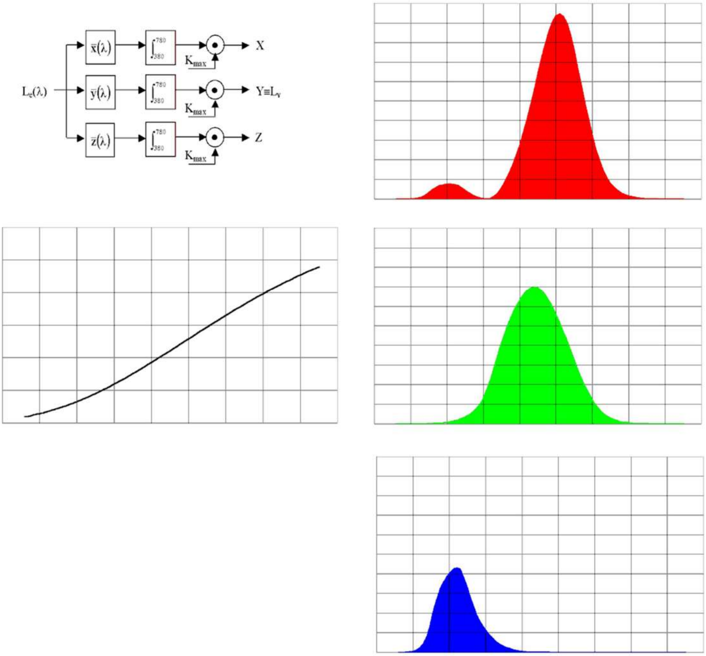

Figure 3.20 - Schematic representation of the tristimulus theory. Electromagnetic radiation with a spectrum $L_e(\lambda)$ is associated with the tristimulus XYZ, which are the area values subtended by the three curves: red, green, and blue.

Their usefulness lies in the fact that they provide a straightforward method for converting the spectral radiance of electromagnetic radiation within the light spectrum into three real numbers XYZ, called tristimulus values. After assigning a spectral radiance $L_e(\lambda)$ it is possible to obtain the tristimulus values XYZ, via the three integrations:

$$X = K_{\max}\int_{380}^{780} L_e(\lambda)\bar{x}(\lambda)d\lambda \;\; ; \;\; Y = K_{\max}\int_{380}^{780} L_e(\lambda)\bar{y}(\lambda)d\lambda \;\; ; \;\; Z = K_{\max}\int_{380}^{780} L_e(\lambda)\bar{z}(\lambda)d\lambda$$

Where K_{max}=683lm/W is the maximum value of the photopic efficacy curve. Based on the above and with mathematical steps that we omit, it can be shown that the tristimulus value Y thus corresponds to the photometric luminance associated with the received spectral radiance. Tristimulus values represent the stimulation that a light signal produces on the three types of LMS cones. These values vary depending on the amount of energy associated with the spectrum.

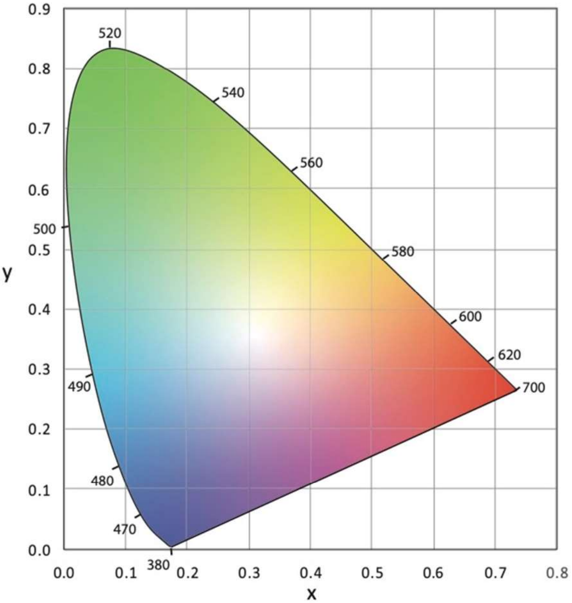

Figure 3.21 - The CIE chromaticity diagram resembles a schematic representation of a painter's palette. In the center is the achromatic color. The colors saturate towards the edges until they become pure, corresponding to monochromatic radiation. The wavelengths of the spectrum corresponding to the pure colors are shown on the border. With the diagram, hue (fundamental wavelength) and saturation (distance from the center) can be determined for color with chromaticity coordinates xy.

To separate the energy information of perceived light from the chromaticity information, the CIE then introduced the xy chromaticity coordinates. The chromaticity coordinates are obtained from the tristimulus values using the following relationships:

$x = X / (X+Y+Z) \ ; \quad y = Y / (X+Y+Z)$

The characteristics of a light signal can be identified by the value triplet (xyY), which identifies color using the two chromaticity coordinates and luminance Y.

The purpose of the presented steps was to obtain three numerical values representing the three fundamental dimensions of color: hue, saturation, and lightness. In this sense, Y, the luminance, is related to the intuitive concept of lightness for surfaces that reflect light or brightness for those that emit it. Unfortunately, xy are not hue and saturation, but they can be linked to these by the chromaticity diagram, which looks surprisingly like a painter's palette. The chromaticity diagram represents hues and saturation levels at constant, unified luminance (i.e., constant energy).

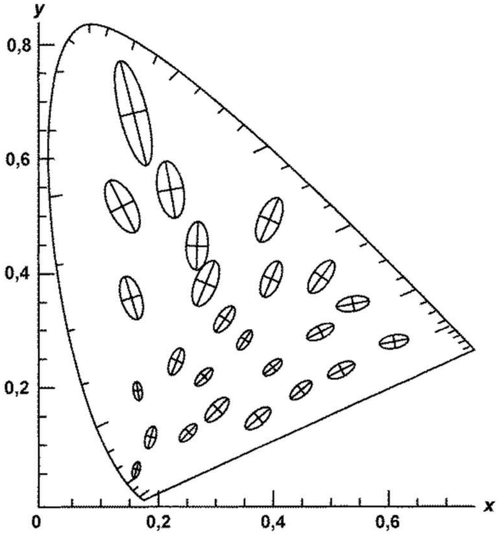

Figure 3.22 - Representation of MacAdam ellipses on the CIE 1931 chromaticity diagram.

The xy value pairs and the XYZ tristimulus values can also be considered the coordinates of a plane or space. In this case, we speak of color space. The CIE XYZ color space is an absolute color space based on observations and experiments on the human visual system. Still, unfortunately, it is not linear in color discrimination and does not lend itself to a perceptual evaluation of the difference between two colors. In other words, equal distances in space do not correspond to similar perceptual color differences, which also applies to the chromaticity diagram. This is clearly visible in the MacAdam ellipses, which indicate certain experimentally determined areas of color that cannot be distinguished (MacAdam, 1942).

Since each point on the chromaticity diagram corresponds to a color, it can be deduced that in the areas of green compared to blue, more xy values produce the same color sensation. This is not to say that humans are less sensitive to green than to blue, but rather that the functions that map the spectral distribution in tristimulus values are not perceptually linear.

One solution to this problem was to modify the functions to deform the CIEXYZ space to obtain a perceptually more linear color space. In 1976, two other color spaces were proposed, CIELUV and CIELAB, obtained from XYZ using mathematical transformations.

In addition to the absolute CIEXYZ color space, the relative RGB and CMY color spaces are commonly used. In fact, when reproducing images, RGB additive synthesis is used on displays, which adds the components of the three colors red, green, and blue to black, and CMY subtractive synthesis for printing, which subtracts the three complementary colors cyan, magenta, and yellow from white. However, the characteristic of these color spaces is that they are relative, i.e., dependent on the color characteristics of the reproduction device used. Indeed, it is very common to find two displays with different color characteristics of the RGB primaries. In this case, the color representation of the same digital image will be slightly different on the two screens. The same applies to inks used in paper printing (Hunt, 2004).

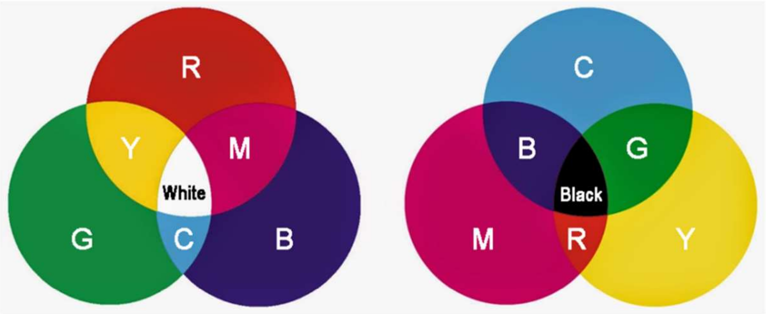

Figure 3.23 - Additive (left) and subtractive (right) color synthesis.

What is important to note about relative color spaces is that the definition of a color made in them is only correct in the context in which the color space is defined. Unfortunately, this is not the case in everyday practice, and this is one of the open problems of digital color reproduction. In typical computer-aided design (CAD) applications, color is always defined and reproduced in terms of RGB space regardless of the displays used, with the result that correct color reproduction cannot be guaranteed on different workstations. CAD often also allows color to be defined using the HLS (Hue, Lightness Saturation) space or the analogous HSV (Hue, Saturation, Value) model, where V is the lightness. However, even these are relative color spaces obtained by mathematical transformations of RGB space.

Some graphics programs allow the color to be defined in the CIEXYZ and CIELAB absolute spaces. Still, to guarantee color correctness, the software is aware of the displays' color characteristics through the information available in the operating system thanks to color calibration procedures. Unfortunately, it is common practice to use CAD and other graphics programs to define colors in terms of RGB spaces and transfer them to different PDs and displays, with the unfortunate result of reproducing different color hues and saturation.

For this reason, with the advent of the WWW, the sRGB color space was introduced, which should be adopted by manufacturers of computer displays and other devices (IEC, 1999). This color space defines:

- The color coordinates of the three RGB primary colors that a display conforming to the standard should have. In reality, virtually no sRGB-compliant display meets this requirement 100%, even right out of the factory, so a color calibration procedure is necessary, which can be done with a colorimeter. This calibration must also be repeated periodically, at least every 6 months.
- The transformation between the CIEXYZ space and the sRGB space.
- The reference white is defined by the standard illuminant D65. This is standard defining daylight with a CCT of 6500K, i.e., with color coordinates similar to a black body heated to 6500 degrees Kelvin (ISO/CIE, 2007).
- The conditions for viewing images on displays are defined by the following five conditions:
    1. the average luminance level of the display is approximately 80cd/m^2;
    2. the average reflectance level of the visible surfaces adjacent to the display is around 0.2;

3. the display has an anti-reflection surface;
4. the display is equipped with black screens that protect against direct light from above and the sides;
5. the ambient light where the display is located should have a CCT of 5000K.

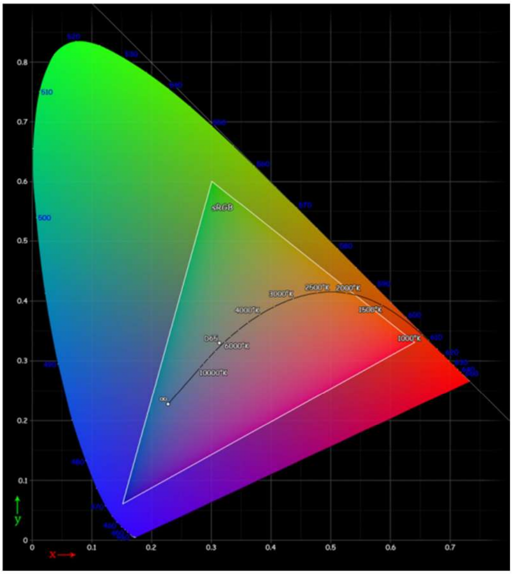

Figure 3.24 - The standard sRGB color space is represented by the triangle within the CIE1931 color space. It can only represent a subset of the hue and saturation levels theoretically perceivable by the human eye.

Figure 3.25 - An sRGB monitor set up at a workstation.

3.6 Limits of colorimetry

The basic CIE tristimulus model is still the reference model for color spaces used in colorimetry. Unfortunately, it has limitations and cannot handle perceptual phenomena such as color constancy (Rizzi, 2021).

Ewald Hering proposed a six-channel model to better explain certain perceptual phenomena: three channels of opposing black-white, red-green, and yellow-blue signals are added to the classical XYZ (Hering, 1964). This model, also supported by physiological studies, tries to explain the fact that the extremes of the two opposite color pairs cannot be perceived simultaneously (Conway, 2002). Namely, one cannot perceive a greenish-red, a bluish-yellow, and so on. Hering's model, in fact, is one of the guidelines for the definition of perceptual spaces such as CIELAB, in which the chromatic coordinates ab represent, with positive or negative values, the red-green, and yellow-blue color oppositions, respectively.

The illumination adaptation mechanism of the human visual system, known as color constancy, is another perceptual aspect that is not covered by the tristimulus model (Monge, 1789; Judd, 1940). Chromatic constancy is the ability to perceive a given surface color even under different lightig spectra, given that the signal that the eye receives derives from the interaction between the spectral reflectance of a surface and the spectral distribution of illuminance (Fairchild, 2013). It follows that chromatic constancy can be considered the ability to receive similar color sensations from an object, even if different spectral distributions come from it due to changes in illuminance. According to this principle, the perceived color of a surface is no longer strictly dependent on the received spectral radiation. Therefore, the tristimulus model is inadequate with its univocity between spectrum and stimulus triplet.

A remarkable aspect of visual perception is that we can retrieve information about the chromaticity of an object regardless of illumination. This is a simple mathematical operation if you know the spectral distribution of the lighting, but the human visual system does this without any prior information about the observed scene. To do this, the perceptual system binds the signal coming from a surface with all signals coming from other objects in the scene and, by comparing them, separates the component due to the illuminant. In other words, if there is more red because of the illuminant, there will be more red on all objects in the scene. Once detected, this component is subtracted from all colors in the scene. This operation is partially justified by the von Kries principle, according to which a chromatic dominant causes a linear shift on each of the tristimulus channels. However, this is an approximation only applicable to weak color dominance. Although the principle remains valid, in reality, there are even more complex non-linearities because the illumination of objects is never uniform. So the color sensation does not derive directly from the retinal signal but is the result of complex cognitive processing of this signal.

To isolate the chromatic dominant, the most common approach is white normalization: for each XYZ color channel, the lightest values in the image are sought, and if they are not already at their maximum value, all channel values are normalized to their maximum value. The principle behind this method is that our visual system maximizes the dynamics of the received visual signal, considering the brightest area of the perceived image as the reference white. Think of a scene containing a sheet of paper, even if it is not perfectly white. If nothing is brighter, it will appear white to us (Marini, Rizzi and Rossi, 1999). In digital cameras, this is called white balance.

3.7 Light spectrum and color

Based on the above, color is not a characteristic of light or objects but a cognitive-perceptual sensation processed by the cerebral cortex. Light is characterized by radiance spectra and surfaces by spectral reflectance. There is a loss of information in the perception of the color sensation associated with the spectrum of a light ray. This is also why the phenomenon of metamerism occurs.

A great deal has been written about the effects of color perception on the human psyche (Xin *et al.*, 1998; Gao and Xin, 2006; Ou *et al.*, 2018; Güneş and Olguntürk, 2020), even in disciplines that have nothing in common with the scientific method. There is also a divergence between the physiology and psychology research methods.

Today, it is not yet possible to give definite answers or formulate exact descriptive models of the human perception of colors and the effects this has on human beings' emotional states because the functioning mechanisms of the brain remain in many respects unknown. Therefore, in this text, we will limit ourselves to the known, objective aspects of lighting and mention some subjective aspects of color.

Since the main requirements of lighting design are based on photometry, we can observe that the current design methodology does not consider two critical aspects of human perception. In the standards, light is described under the assumption that the observer is always in a photopic vision condition. And this is not always true. Furthermore, considering only the photopic hypothesis and ignoring the shape of the light spectrum can lead to incorrect assessments of color rendering index (CRI)(CIE, 2017), the actual efficiency of light sources, and the psycho-physiological effects light can have on humans.

To further complicate the picture outlined above, it should also be noted that between photopic perception, which mainly involves the cones, and scotopic perception, which involves the rods primarily, there is also an intermediate level called mesopic.

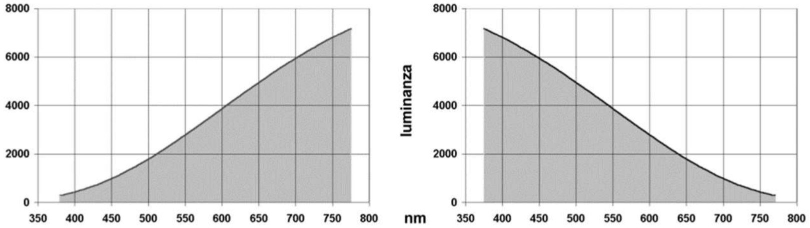

Figure 3.26 - SPD of two lights. On the left is yellow-red dominant radiation. On the right is a green-blue dominant one. The two lights have the same luminance, L=0.001398cd/m^2, on the borderline between scotopic and mesopic vision. For this reason, the blue-green one will appear brighter.

Experiments have shown, for example, that for the visual tasks in night-time driving, which involve the periphery of the visual field, where there are more rods, to detect the arrival of moving obstacles on the road, white light is better than yellowish light (Akashi, Rea and Bullough, 2007). This is because yellow light is less perceptible at low (nearly mesopic) luminance levels than white light, which is more visible at night. This contrasts with the efficiency levels advertised in the past by manufacturers, who presented sodium lamps as much more efficient than white metal halide lamps. Actually, the comparison between the efficiency levels of the two lamps is made in photometric terms. Therefore, it does not take into account that the vision of the areas illuminated by the sources may be in mesopic or scotopic vision conditions (Rea *et al.*, 2004). Today, with the advent of LEDs, this diatribe has been superseded, and the use of white light in street lighting is now a given.

To evaluate aspects of color perception, it is interesting to analyze how light interacts with materials. We have already seen, talking about color constancy, that the HVS compensates for the effects of color dominance due to lighting. This effectively eliminates most of the color variation caused by the spectra of light sources. In fact, if you look at the spectral emissions of commonly used white light sources, you will see that they are highly different from each other and even more different from natural light. As already mentioned, our perceptual system can compensate for most of these effects, and a clear demonstration of this phenomenon is in the vision of the color white.

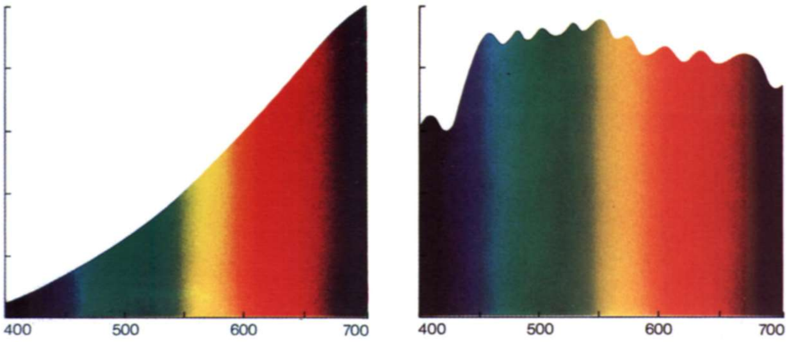

Figure 3.27 - Relative SPD of light emitted by a tungsten incandescent source (left) with CCT=2700K and natural light (right) with CCT=6500K.

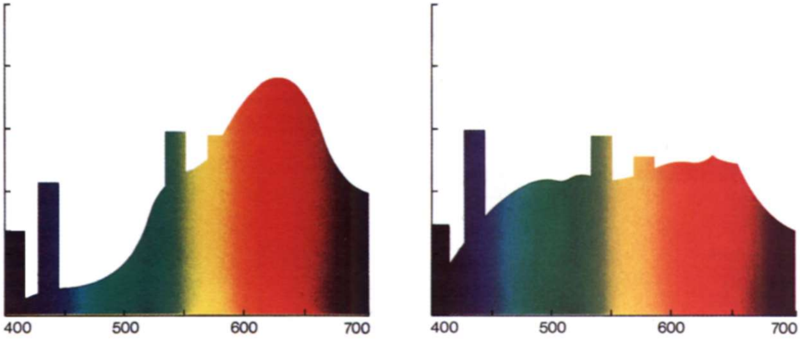

Figure 3.28 - Relative SPD emitted by white fluorescent lamps. Right CCT=3000K, left CCT=5000K.

The concept of absolute white is purely theoretical since the various sources of white light have different spectral distributions, with warm hues such as red and yellow or cool hues such as blue and green predominating. However, in all cases, if a surface reflects all wavelengths of the spectrum in the same proportion, we will perceive it as white. Perhaps warm white if lit with warm tones or cool white if lit with cold tones, but still white.

The hue of the white light source is associated with the CCT parameter. A source with a CCT=2700K is perceived as warmer than a 5000K source.

It is highly complex to determine which CCT is the most appropriate for the various visible tasks. The aspects to be considered when choosing the CCT of lamps to depend on many parameters, but two are the main ones. The colors of the objects in the room to be lit and the type of psycho-perceptual effect you want to stimulate the observers.

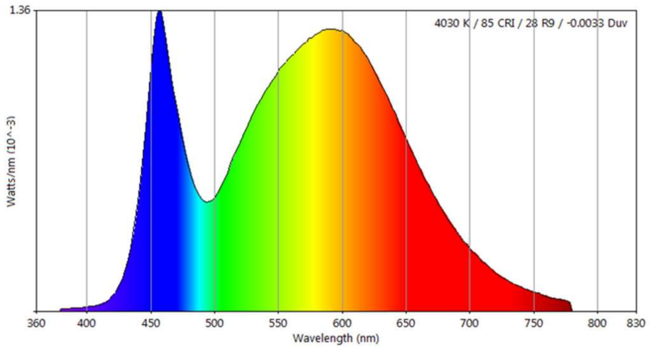

Figure 3.29 - Power spectrum emitted by a white LED with CCT=4030K and CRI=85.

For the first aspect, reference can be made to the established lighting design practice in the various artificial lighting applications (Flynn and Spencer, 1977). If, for example, you want to enhance the color characteristics of objects or structures, you can follow the rule that divides surface colors into three groups:

- To illuminate predominantly warm colors such as red, orange, and yellow, i.e., wavelengths above 565nm, it is preferable to use lamps with a warm hue and CCT between 2500K-3300K.
- For the lighting of predominantly cool colors such as violet, blue, light blue, cyan, and green, i.e., wavelengths shorter than 565nm, it is preferable to use lamps with cold tones and CCT between 5000K-6000K.
- For objects and rooms without a marked warm or cold color preponderance, it is preferable to use lamps with an intermediate CCT between 3400K-5000K.

Following the old Kruithof rule, warm-toned light sources make people see better at lower illuminance levels than cool-toned ones, and vice versa (Kruithof, 1941), even if some researchers disagree with this assumption (Fotios, 2001; Viola *et al.*, 2008; Viénot, Durand and Mahler, 2009).

In a room characterized by intense, highly saturated colors, the use of warm color sources increases the characterization and strength of the room. In contrast, cool tones soften the perception and increase the spaciousness feeling. In addition, using low-saturated light-colored materials for structures and furnishings facilitates diffuse inter-reflections of lighting, i.e., the diffusion of indirect light that softens the cut of the shadows (Long, 1937). In the opposite case, there are scenographic effects of sharply cut lighting and shadows, increasing the dramatic perception and the 3D perception of the world (Moon and Spencer, 1951).

The ceiling reflectance deserves a special mention (Levin, 1987). In workplaces, this should be bright so as not to overwhelm the occupants with a sense of oppression, without however indulging in the opposite extreme with a mimetic and elusive appearance that can produce a feeling of escape into immense spaces in which the occupant cannot carve out his own comfortable working space (Küller *et al.*, 2006). In subjects predisposed to these disorders, in the first case, limited latent effects of claustrophobia can be induced, while in the second, agoraphobia. Light, through direct or indirect illumination, with the ceiling as its reference point, can emphasise or lower these sensations. A floor that is too light and a ceiling that is too dark, reversing the natural light conditions under which we evolved, can generate a perceptual feeling of disorientation and vertigo (Flynn *et al.*, 1979).

Having established that light can emphasize or soften the color tones of an environment, it can be observed that many authors associate subjective emotional feelings with various colors (Kwallek *et al.*, 1996; Küller *et al.*, 2006; Odabaşioğlu and Olguntürk, 2015; Tantanatewin and Inkarojrit, 2016). However, it should be noted that this is a very controversial issue and is still the subject of research in psychology (Valdez and Mehrabian, 1994; So and Leung, 1998; Wilms and Oberfeld, 2018).

But above all, it is imbued with strong cultural values, and therefore it changes according to countries and continents (Küller *et al.*, 2006; Gao *et al.*, 2007). Red is associated with strong but ambivalent feelings, which can represent danger or the warm welcome of the hearth (Elliot *et al.*, 2007). Green, the color of nature, induces feelings of calm and balance (Hårleman, Werner and Billger, 2007), but in some cases, it can also be associated with anger (Hupka *et al.*, 1997). Yellow symbolizes joy and life (Pastoureau, 2019), while blue, like black and other dark colors, might be associated with negative feelings (Elliot, 2015). Still, it depends on the application context because, in fashion, they are considered elegant (Koh, 2019). Orange, which mediates between the intense feelings of red and the joy of yellow, is associated with triumph, positive mystical glorification (Bortoli and Maroto, 2008) and, like blue, vastness.

However, white and strongly desaturated light colors play a significant role in interior and exterior design (Miller, 1997). Being colors with high reflectance factor, they are helpful for light reflection and diffusion and are also considered stimulating for intellectual activities in the attention restoration theory (Stevenson, Schilhab and Bentsen, 2018). However, going back to cultural meanings of colors, for example in China, white is considered the color of mourning.

3.8 The color rendering open problem

A critical parameter for describing the colorimetric characteristics of light sources is the CRI. This represents the ability of a light source to render the color of objects compared to the color rendering under a reference source. Typically, natural light has the highest color rendering, whereas a low-pressure sodium lamp has the lowest CRI=0. In artificial sources, color rendering and efficiency are generally inversely proportional. For example, incandescent and halogen lamps, which are the least efficient, have the best CRIs. This index is evaluated based on the ability to render a set of 8 colors chosen in the Munsell color system against a CCT-dependent reference source. The method calculates the chromaticity differences of the color samples as the illuminant changes from the reference source to the test source. If the CCT<5000K, the reference source is the blackbody spectrum of equal CCT, but if the CCT>5000K, the reference source chosen is a daylight D-series illuminant (ISO/CIE, 2007) with a CCT similar to that of the tested lamp.

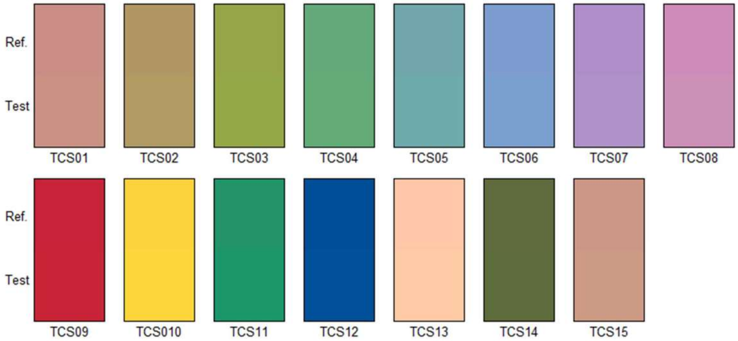

Figure 3.30 - Top: The eight colors from the Munsell atlas used to calculate the CRI. Below are the seven additional colors.

The CRI of natural light and a halogen lamp is considered the best and have CRI=100. In contrast, the color rendering of a low-pressure sodium vapor lamp, which has an almost monochromatic spectral output, is zero. The color rendering index can intuitively be imagined as a valuable tool in assessing the spectral completeness of a light source: the more irregular and discontinuous a spectrum, the lower the CRI.

However, it is essential to note that the CRI, although still widely used as a reference standard, is a tool considered obsolete by many researchers because it cannot adequately describe the actual color rendering of the new LED sources. It has been challenged by many scientific studies (CIE, 2007; Davis and Ohno, 2010; Fumagalli, Bonanomi and Rizzi, 2015). Indeed, the CRI was defined many years ago, when there were only a fraction of the light sources available on the market today. Within the CIE, working groups have been set up over the last 20 years to define a new method for describing the color rendering of artificial light sources. Still, no results have been achieved, as there are significant commercial interests in maintaining the status quo represented by the CRI.

In the USA, a new method of describing color rendering was adopted in 2015 and updated in 2020, with the TM-30-20 standard, likely to become the de-facto standard worldwide (IES, 2020).

	CIE CRI (1974)	**TM-30 (2020)**
Color space used for calculations	CIE UVW 1964	CIECAM02 (2002)
Number of colors used	8	99
Indexes used to describe the yield	1 alone: R_a	2 indexes: R_f R_g in addition to the graphical representation
Reference illuminant	Black body or daylight with 5000K step variation	Black body or daylight with gradual variation between 4500K and 5500K

Figure 3.31 - The main differences between the two standards CIE CRI and IES TM-30-20.

In particular, this method describes the color rendering using two indexes. The first R_f, with values from 0 to 100, represents the fidelity with which a light source allows us to see colors without changing the hue. The second index R_g, with values less than or greater than 100, will enable us to assess whether a light source can increase or decrease the level of saturation with which we perceive colors. In addition to these two indexes, there is a color distortion icon graph.

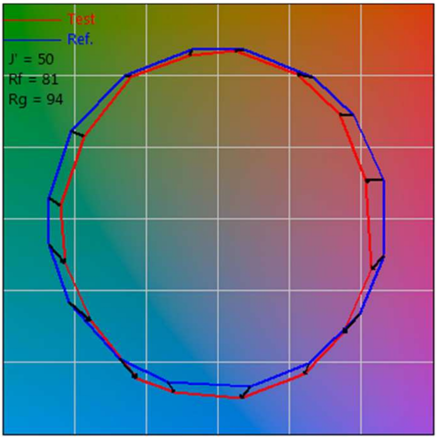

Figure 32 - The TM-30 color distortion icon of a commercial light source characterized by R_f=81 and R_g=94. The blue graph represents the chromaticity coordinates of the color samples illuminated by the reference source. The red graph represents the chromaticity coordinates of the colors under the test source. When there is a rotation in the position of the vertices (colors), it means that we are losing hue fidelity. When a color moves inwards within the blue circle, it loses saturation (Rg<100), but if it moves outwards within the blue circle, the light source is increasing its saturation (Rg>100).

In an attempt to remove the well-known problems of the CRI, the researchers of the European Broadcasting Union, based on some preliminary studies (Sproson and Taylor, 1971), developed two indexes for the television sector, the Television Lighting Consistency Index (TLCI) in 2012 and the Television Luminaire Matching Factor (TLMF) in 2013 (EBU, 2012, 2016).

TLCI-2012 removes the human observer regarding color discrimination, entrusting the evaluation to a spectral, radiometric measurement of a sample, the first 18 patches of the Macbeth ColorChecker (excluded the greyscale), compared with a reference sample. The chromaticity of the reference used can be on the Planckian locus, if the test source CCT is below 3400K, on the Daylight locus, if above 5000K, or a linear interpolation between the two, if the test is between 3400 and 5000 K. The measured values are then processed by a specific software that simulates the typical characteristics of the cameras and displays where the image will be played. For cameras, the considered parameters are responsivity curves, linear matrix, and optoelectronic transfer function or gamma-correction. As for the displays, instead, the parameters are the non-linearity or electrooptical transfer function, the chromaticities of the set of primaries, and the white balance point. Once the calculations have been performed, the software returns a unique value, Qa, from 0 to 100, which indicates how feasible it is to attempt a chromatic correction on the source. The results must be interpreted according to the type of production; for example, film-type shots have a much more restrictive reading than live shots with different cameras.

The TLMF-2013 is very similar to the previous one. The main difference is that instead of an ideal reference source, a real one is used, which can be chosen according to the type of test source and specified in the results. The aim is to be more direct than TLCI in evaluating the mix between different sources. While TLCI is helpful for equipment manufacturers, TLFM is aimed at practitioners to predict a combination of sources before arriving in the studio, where it is usually too late to intervene (Wood, 2013).

A further index is the Spectral Similarity Index (SSI), developed in 2016 by experts from the Academy of Motion Picture Arts and Sciences (SMPTE, 2020). In the SSI, to avoid the excess of variability given by the human evaluation or numerous and different cameras (which may have spectral sensitivities that reach out of the visible spectrum), the variance of the test source related to the reference source is taken into account. Therefore, the spectral sensitivities of the various devices are not considered, but instead, how much, in some areas of the spectrum, the test source spectrum differs from that of the reference source: incandescent or daylight. The purpose was to create a so-called "confidence factor." The result is an index (0-100) on the probabilities of the test source to render the colors in the same way as the reference.

3.9 Conclusions: real vs virtual perception

From what has been illustrated in this and previous chapters, the development of the lighting design methodology over the last 20 years has radically changed due to the introduction of IT into the design process, including the introduction of virtual reality.

In computer graphics, many texts are available that explain the mathematics used to produce colored renderings. However, even the best technologies available today are severely limited in their ability to deal with the radiometric and colorimetric aspects of light. The reason for these limitations lies in the extreme mathematical complexity of the models in question, which get simplified to the detriment of precision, thus moving away from the main objective of rendering used in the design process: photorealism to achieve virtual prototyping. To define the problem, we state that a synthetic image is only perfectly photorealistic if it produces in the human observer a visual stimulus equal to that produced by the reality that the image is intended to represent. It should be made clear that a system capable of delivering perfectly photorealistic renderings for environments of arbitrary complexity has not yet been created.

However, the common thread in the description of the image synthesis problem is the calculation of light radiance, which is distributed over an environment. In everyday reality, light transports information that the human observer receives to perceive the brightness and chromaticity of images.

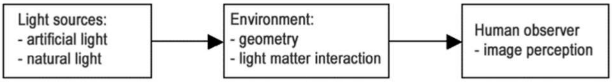

Figure 3.33 - System describing the process of image perception in reality.

Light is produced by natural sources, such as the Sun, or artificial ones, such as luminaires, then interacts with the environment characterized by the presence of different materials, with arbitrary shapes, and finally reaches the retina of the human observer who, from the section of a conical beam of rays, processes the light signal to produce the psycho-physiological cerebral sensation known as an image.

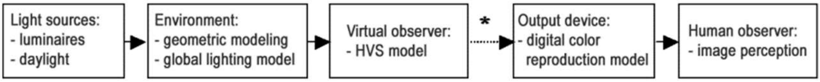

Figure 3.34 - System describing the light path in photorealistic rendering. In the transition from the virtual observer to the output device, light is not defined by the SPD but by a triple value in the relative digital RGB color space, resulting in a loss of information, shown in the figure by a *.

This process has to be simulated in photorealistic rendering, starting from a set of photometric, radiometric and geometric data assigned by the designer. These describe reality to produce the same visual sensation that one would have of the real world described by the data through a digital output device (Marini, Rizzi and Rossi, 1999). This process can be described by five steps:

1. Since light is electromagnetic radiation with a wavelength range of 380-780nm, the data on light sources can be described using the standards of lighting technology, which is based on photometry and radiometry.

2. The foundations of the geometric description of the environment are based on analytical geometry, which allows arbitrary shapes to be modeled using parametric surfaces. Under the assumption of an ideal surface, the interaction between light and matter can be described in physics using the Fresnel functions for dielectrics and conductors. Still, these are difficult to deal with in the case of real materials. In the more general case of real surfaces, it is described in radiometry using reflectometry functions such as the Bidirectional Reflectance Distribution Function (BRDF). Unfortunately, this is not known analytically and is expensive and difficult to measure for surfaces of everyday design.
3. The HVS can be described by the CIE tristimulus theory, which is the basis of colorimetry. Light is colorimetrically defined as a triplet of RGB values in the software. Colorimetry is not enough: cognitive perception should also be considered (McCann and Rizzi, 2011).
4. Unfortunately, the digital RGB color space used to generate colored light on displays is relative. In the transition from the virtual observer to the output device, the light is described by spectral radiance but with a triple value, leading to a loss of information and problems with color correctness.
5. For each sample point of the rendering, the human observer receives, from the display, the light levels of the three color classes, which are integrated by the HVS to obtain the perceived image.

Today, a wide range of software CAD is available that allows objects and environments to be geometrically described and rendered. On the one hand, these systems offer considerable potential in describing geometry, allowing objects of arbitrarily complex shapes to be modeled using parametric surfaces. On the other hand, however, they have significant limitations in the photorealism of the renderings that can be obtained in terms of the chromatic appearance of the materials and light distribution. In fact, these systems allow us to get stunning renderings from an impressionistic point of view, but with low information value concerning the reality we want to represent.

The reasons why these commercial software CADs provide a low level of photorealism are the need to produce images in a limited time or even in real-time for the realization of animations at 25 frames per second, and this has led to the development of simplified and empirically formulated global illumination models, without relying on a physically correct approach to the calculation of light-matter interaction.

Figure 3.35 – Rendering an interior design project using the Photon Mapping calculation method. Courtesy Juan Manuel Torres.

In practical implementation, since the displays are based on the additive synthesis of the three RGB colors, light and materials are not described by their spectral characteristics but by triplets of values that try to describe the color and reflectance characteristics of the material. With this technique, light sources, materials, and the lighting model are expressed in terms of the representation model, which is based on the RGB digital color space. This simplification allows images to be calculated very quickly. Still, because it expresses real-world phenomena and physical characteristics in terms of tristimulus elements, it cannot calculate the distribution of light in a physically correct way. In radiometric reality, the interaction between light and materials is not in colorimetric terms.

Another crucial aspect influencing photorealistic rendering is the calculation of global illumination. Objects are illuminated not only by the light coming directly from lighting sources but also by the light reflected by or transmitted from other surfaces. This component is referred to as indirect illuminance and, in some cases, can account for more than 50% of the illuminance in a room. For this reason, the physically correct calculation of the global illumination model is of primary importance in software systems supporting the quantitative and qualitative evaluation of lighting design, while it is often ignored in software in order to create beautiful images.

The calculation of global illuminance requires the use of software that applies complex global illumination models such as radiosity (Goral *et al.*, 1984), Monte-Carlo Ray Tracing (Shirley, Wang and Zimmerman, 1996), and Photon-Mapping (Jensen, 1996). These enable the calculation of specular and diffuse inter-reflections of light between objects and transparent media. Today, these models have been integrated into the solution of the so-called rendering equation (Kajiya, 1986).

This book does not detail the mentioned global lighting models but instead describes how these IT tools have changed the lighting design process.

3.10 Conflict of interest declaration

The author declares that nothing has affected his objectivity or independence in the production of this chapter. Neither the author nor his immediate family member has any financial interest in the people, manufacturer or topics involved in this article. The author also declares that no conflict of interest, including financial, personal, or other relationship with other people and organizations, could inappropriately influence, or be perceived to influence, this work.

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Chapter 4

Lighting design constraints and methods

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Abstract

This chapter focuses on the constraints that exist and shape the lighting design process. The past decade has seen the update and proliferation of new standards that define quantitative requirements and introduce qualitative lighting criteria. This chapter also pays attention to methods resulting from the environmental sustainability issue, the aspects relating to energy savings, the end-of-life of lighting products, and the regulatory situation. Finally, we will see how all these constraints affect the objectives and methods of lighting design.

Keywords

Lighting standard, sustainability, light pollution, design methods

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4.1 Introduction to regulatory bodies for lighting

According to the Gaia hypothesis, living organisms on Earth interact with the surrounding inorganic components to form a complex synergistic and self-regulating system, which helps maintain and perpetuate the conditions for life on the planet (Lovelock and Margulis, 1974; Lovelock, 2000).

The optimization of resources according to pre-assigned constraints is the principal activity of the lighting design process. Thinking also about Gaia, external constraints come from the environment understood as a set of related subsystems:

- Sociosphere: covers cultural and social aspects in the organization of human activities.
- Technosphere: defines the economic, scientific, and technological aspects of human culture.
- Biosphere: is the environment in which we live, understood as the set of renewable and non-renewable natural biological resources.
- Geosphere: covers aspects related to the territory and its management in relation to other subsystems.

Other so-called internal constraints are self-imposed by the designer on his own working methods and strongly contribute to characterizing the designer's style.

Within the framework of external constraints induced by the socio-economic sphere, a distinction can be made between those imperative, such as legal obligations, and those of a voluntary or incentive nature represented by industry regulations.

European, Italian and regional legislation on lighting design is highly fragmented, with a series of laws, law decrees, and ministerial circulars that, in some cases, leave room for doubts about interpretation and clash with the technical regulations of the same sector. The central theme of safety and health of the spaces to be illuminated with artificial and/or natural light is the main thread common to all legislation. However, it can be observed that this is divided into three areas of intervention concerning lighting criteria: the electrical supply system, fire prevention systems, and the elimination of architectural barriers. This legislation is constantly evolving.

The most consolidated part of the sector's legislation relates to the area of electrical installations, which implements the directives of the European Union concerning the safety of power supply systems and electrical equipment and, therefore, affects both lighting designers and manufacturers.

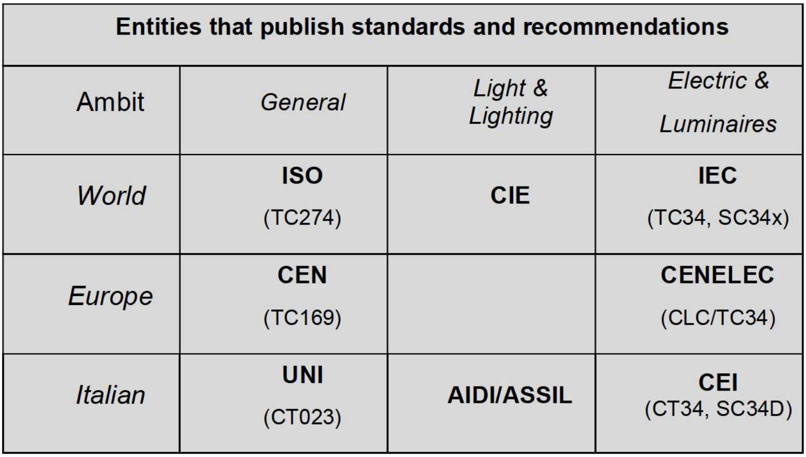
In Italy and other countries, some ministerial circulars and decrees focus on fire prevention and eliminating architectural barriers, including lighting aspects.

The external constraints coming mainly from the technosphere and partly from the sociosphere are represented by rules, recommendations, and standards issued by various standardization, unification, and research bodies at the national and international levels. It should be noted that although standards are generally of a voluntary and incentivizing nature, they are the foundation for any project activity. Exceptions to this are standards issued on behalf of the European Commission, complementing directives, which are in any case mandatory in the member states. Therefore, the production and exchange of goods in the global market and, thus, the adherence of products and projects to regulations or, in some cases, even the ability to anticipate rules rather than having to chase them, represent an opportunity and a stimulus from the perspective of innovation, which produces positive results in competitiveness (EU, 2012). The continuous evolution of scientific research in the field of lighting and the consequent activity of updating or publishing new standards are, in fact, one of the stimuli provided by public actors for lighting innovation.

The area of lighting regulation is complicated by the number of bodies involved in researching, drafting, publishing standards, and recommendations. First of all, three different levels of competence can be observed in administrative terms: World, European, and Italian. At these levels, the three general standardization bodies are ISO (International Organization for Standardization), CEN (Comité Européen de Normalisation), and UNI (Ente Nazionale Italiano di Unificazione). As in a game of Russian dolls, UNI participates in the works of CEN, and CEN, in turn, participates in the works of ISO. Directives issued by ISO are transposed by CEN, and those published by CEN in the EU are transposed by UNI in Italy. The general rule is that a standardization entity at a lower level cannot issue a standard on its own initiative on a subject for which a similar standard has already been published or is being developed at a higher level, as it is obliged to transpose it. A standardization entity could work and publish a standard only in the absence of a higher standard.

To complicate the situation even further, the two areas of lighting and electrical engineering are affiliated to other sectoral bodies at various levels, which participate in the works of the committees of the three main bodies ISO, CEN, and UNI. For the electrical engineering sector, IEC (International Electrotechnical Commission) exists at world level, CENELEC (Comité Européen de Normalisation Électrotechnique) at the

European level, and CEI (Comitato Elettrotecnico Italiano) at the national level. For the lighting and photometric sector there is the CIE (Commission Internationale de l'Éclairage) at world level and at Italian level AIDI (Associazione Italiana di Illuminazione) in collaboration with ASSIL (Associazione Nazionale Produttori Illuminazione) participates in the work of the CIE.



Entities that publish standards and recommendations			
Ambit	*General*	*Light & Lighting*	*Electric & Luminaires*
World	**ISO** (TC274)	**CIE**	**IEC** (TC34, SC34x)
Europe	**CEN** (TC169)		**CENELEC** (CLC/TC34)
Italian	**UNI** (CT023)	**AIDI/ASSIL**	**CEI** (CT34, SC34D)

Figure 4.1 – Organizations at the World, European and Italian levels dealing with lighting and luminaires.

In order to understand which sources to draw on for the relevant regulations, it is also appropriate to outline the relationship between these bodies on lighting topics. The ISO works on light and lighting for a few scientific standards published with CIE. The CIE is mainly concerned with research and scientific essay on light, lighting, color, and visual perception, published in scientific papers, technical reports, and international standards.
The CEN prepares European standards, on behalf of the European Commission, also based on the scientific publications of CIE. UNI participates in the work of CEN, transposes its standards, publishes them in Italy, and prepares new standards only in case of the absence of CEN standards. In addition, some standards promulgated by CEN on behalf of the European Commission take on the role of EU laws, with which the EU member states must comply. Other CEN standards are voluntary and mainly aimed at harmonizing the EU market. The scientific activity coordinated at the World level within CIE sees in Italy the participation of the CIE National Committee through AIDI in collaboration with ASSIL.

The work of these bodies is also divided into technical committees and sometimes even subcommittees. The ISO technical committee 274 works on light and lighting for some World standards published together with CIE. Within CEN, the technical committee TC169, which started its works in 1990, is responsible for light and lighting. These committee results are often slow due to the time it takes to obtain the consensus of all EU member states. Also, in 1990, within UNI, the technical commission U29, now renamed "CT023 Luce e illuminazione", began its work on topics concerning light and illumination in the fields of vision, photometry, and colorimetry. This involves natural and artificial radiation in the spectral regions of the ultraviolet, visible, and infrared, regarding the applications involving all uses of light indoors and outdoors, including environmental and aesthetic effects. In particular:

- Terminology and quality criteria of lighting technology.
- Lighting for homes, workplaces, schools, sports facilities and environments, roads and tunnels.
- Reference lighting bodies for colorimetry.
- Photometry of luminaires and general photometric criteria.
- Catadioptric reflection.
- Light pollution.

To give a complete picture of the areas of intervention of the standards in the lighting sector, we observe that these activities are carried out by UNI CT023 commission, divided into fifteen working groups plus a central coordination group:

- GL01 General terms and quality criteria – Definitions.
- GL02 Lighting of work and school premises.
- GL03 Emergency lighting in buildings (UNI - CEI mixed).
- GL04 Sports lighting.
- GL05 Street lighting (mixed Light and Lighting / Road construction and civil infrastructure works).
- GL06 Gallery lighting.
- GL07 Photometry and colorimetry.
- GL08 Light pollution.
- GL10 Energy saving in buildings.
- GL11 Daylight.
- GL12 Lighting design.

- GL13 Photometric performance.
- GL14 Cultural Heritage Lighting (mixed Light and Lighting / Cultural Heritage).
- GL15 Regulatory activity in the field of non-regulated professional activities (APNR): Lighting Designer.
- GL16 Validation methodologies of lighting CAD software.

4.2 Framework of standards for lighting

The works of the CT023 committee have produced several already published standards, and work on new draft standards is also ongoing. A crucial aspect of the regulatory framework is that these standards have only been published in the last fifteen years. Most of them, i.e., those most interesting for lighting design, has been updated in recent years. These standards can be divided into five main categories: general lighting standards, luminaire measurement standards, indoor lighting standards, outdoor lighting standards, and standards for materials and colors concerning lighting. Few lighting designers know them all in detail, but it is undoubtedly helpful to know what they are to have reference points for lighting design in various applications. Some of them are only in the Italian language.

General lighting standards:

- UNI 11630:2016 Luce e illuminazione - Criteri per la stesura del progetto illuminotecnico.
- UNI EN 12665:2018 Light and lighting - Basic terms and criteria for specifying lighting requirements.
- ISO 80000-7:2019 Quantities and units Light and radiation
- UNI 11142:2004 Luce e illuminazione - Fotometri portatili - Caratteristiche prestazionali.

Luminaire measurement standards:

- EN 13032-1:2004+A1:2012 Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 1: Measurement and file format.
- EN 13032-2:2017 Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 2: Presentation of data for indoor and outdoor work places.
- EN 13032-3:2007 Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 3: Presentation of data for emergency lighting of work places.

- EN 13032-4:2015+A1:2019 Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 4: LED lamps, modules and luminaires.

Indoor lighting standards:
- EN 15193-1:2017+A1:2021 Energy performance of buildings - Energy requirements for lighting - Part 1: Specifications, Module M9.
- CEN/TR 15193-2:2017 Energy performance of buildings - Energy requirements for lighting - Part 2: Explanation and justification of EN 15193-1, Module M9.
- EN 1838:2013 Lighting applications. Emergency lighting.
- UNI CEI 11222:2013 Luce e illuminazione - Impianti di illuminazione di sicurezza degli edifici - Procedure per la verifica e la manutenzione periodica.
- EN 12464-1:2021 Light and lighting - Lighting of work places - Part 1: Indoor work places.
- EN 1837:2020 Safety of machinery - Integral lighting of machines.
- UNI 10840:2007 Luce e illuminazione - Locali scolastici - Criteri generali per l'illuminazione artificiale e naturale.
- UNI 11165:2005 Luce e illuminazione - Illuminazione di interni - Valutazione dell'abbagliamento molesto con il metodo UGR.
- UNI 8097:2004 Metropolitane - Illuminazione delle metropolitane in sotterranea ed in superficie.

Outdoor lighting standards:
- EC 1-2017 UNI 11248:2016 lluminazione stradale - Selezione delle categorie illuminotecniche.
- UNI/TS 11690:2017 Illuminazione stradale - Definizione e valutazione del “fattore di visibilità di oggetti” (FVO) in impianti di illuminazione stradale realizzati secondo la UNI 11248.
- EN 13201-2:2015 Road lighting - Part 2: Performance requirements.
- EN 13201-3:2015 Road lighting - Part 3: Calculation of performance.
- EN 13201-4:2015 Road lighting - Part 4: Methods of measuring lighting performance.
- EN 13201-5:2015 Road lighting - Part 5: Energy performance indicators.
- EN 12464-2:2014 Light and lighting - Lighting of work places - Part 2: Outdoor work places.
- EN 16276:2013 Evacuation Lighting in Road Tunnels.

- UNI 11095:2021 Luce e illuminazione - Illuminazione delle gallerie stradali.
- UNI 11431:2021 Luce e illuminazione - Applicazione in ambito stradale dei dispositivi regolatori di flusso luminoso.
- EN 12193:2018 Light and lighting - Sports lighting.
- UNI 10819:2021 Luce e illuminazione - Impianti di illuminazione esterna - grandezze illuminotecniche e procedure di calcolo per la valutazione della dispersione verso l'alto del flusso luminoso.

Standards for materials and colors:
- EN ISO/CIE 11664-1:2019 Colorimetry - Part 1: CIE standard colorimetric observers.
- EN ISO 18314-1:2018 Analytical colorimetry - Part 1: Practical colour measurement.
- EN ISO 18314-3:2018 Analytical colorimetry - Part 3: Special indices.
- EN 16268:2013 Perfomance of reflecting surfaces for luminaires.
- UNI 10701:1999 Colorimetria - Campione di Riferimento Secondario (CRS) - Interpretazione ed utilizzo dei dati colorimetrici all'atto della richiesta di un prodotto con colore a campione.
- UNI 10623:1998 Colorimetria - Compensazione delle differenze di brillantezza (gloss) nella misurazione del colore delle superfici.
- UNI 9810:1991 Denominazione dei colori.
- CNR UNI 10017:1991 Illuminotecnica. Illuminanti A e D65 per la colorimetria.
- CNR UNI 10019:1991 Illuminotecnica. Osservatori CIE per la colorimetria.
- UNI 7948:1987 Colorimetria. Termini e definizioni.
- UNI 8813:1986 Edilizia. Sistema di specificazione del colore.

Out of these, we can identify 4 as fundamental to the lighting designer's skill set out of these standards.
The recently updated EN 12464-1:2021 standard provides the requirements for executing, operating, and verifying artificial lighting systems in civil and industrial interiors, excluding environments and areas concerned by specific regulations. It applies entirely to new installations and to radical conversions of existing installations. It sets out how to choose, evaluate and measure the photo-colorimetric quantities needed to define the characteristics of an artificial lighting system for interiors. The measurement and evaluation can cover both the verification of the design of

new installations and the control of existing ones to achieve homogeneous quality levels concerning the different visual tasks.

As far as exteriors are concerned, the EN 13201 and UNI 11248:2016 series of standards indicate the quantity and quality requirements for street lighting design, testing, and maintenance of a lighting system. These requirements are expressed in terms of the level and uniformity of luminance of the road surface, roadside lighting, glare limitation, and optical guidance. They are provided according to the road class, which is defined concerning the type and density of vehicular traffic. Also critical is the "UNI 11630:2016 Light and Lighting - Criteria for drawing up a lighting design" standard, which we will discuss in more detail later.

The framework of standards and inter-agency relationships outlined so far only applies to the performance and photometric aspects of lighting, as everything related to electrical safety falls within the scope of IEC, CENELEC, and CEI. For some years now, the Italian CEI standards have coincided with those issued by CENELEC and are published in Italian and English. The works of IEC are organized in many committees. The one of most significant interest for lighting applications is TC34 Lighting, which in turn is divided into four subcommittees:

- SC 34A Electric light sources.
- SC 34B Lamp caps and holders.
- SC 34C Auxiliaries for lamps.
- SC 34D Luminaires.

To date, dozens of standards are available from the work of the TC34 committee and its subcommittees, which define many requirements and characteristics of luminaires. These standards are of specific interest to manufacturers in the industry and to lighting product designers. It is not the purpose of this text to list them, but it may be helpful to know that they can be easily found also on the CEI website dedicated to standards; by entering the acronym CEI 34 as a search keyword, it is possible to obtain a list of the standards to which the technical committee 34 and its subcommittees have collaborated.

4.3 Light pollution

The UNI 10819:2021 standard deals with the issue of light pollution that prevents the night vision of the sky (Riegel, 1973) and has adverse biological effects, too (Longcore and Rich, 2004; Navara and Nelson, 2007). It prescribes requirements for assessing outdoor lighting installations to limit the upward dispersion of luminous flux. It does not consider the limitation of the night sky luminance due to the reflection of illuminated surfaces or special local conditions such as air pollution. The standard only applies to new outdoor lighting installations. Street lighting aims to promote the safety of pedestrians, property, and, of course, vehicular traffic at night. However, even with professionally designed and constructed lighting systems, there is always a partial light emission into the sky. This is due to the natural reflection of light on the road surface and buildings. In particular, it is estimated that 10% of the light received is reflected upwards by the dry, or more, on wet, asphalt (Frederiksen and Sørensen, 1976; Bodmann and Schmidt, 1989). Some of the upward luminous flux can also escape directly from luminaires used in public lighting. The light dispersed upwards diffuses among the atmospheric dust also depends on the humidity level in the air and is partly sent back down to the ground. The result of this phenomenon is that at night the background luminance of the sky can become higher than that of the sky, preventing the vision of the stars. This is even more true near large public lighting systems in urban areas. Indeed it is not the light that pollutes, but the light highlights the dust pollution in the air. Light pollution also generates costs for the negative impacts on wildlife, health, astronomy, and wasted energy (Gallaway, Olsen and Mitchell, 2010).

Figure 4.2 – Night photograph of Europe as seen from space.

The level of light pollution is now such that it is incompatible with astronomical observation. In particular, there are at least two schools of thought on the subject (Clanton, 2014). The first one argues that light pollution is inevitable, and therefore the solution is to move astronomical observatories to mountain tops, as in the Andes near the Atacama Desert in Chile, away from plains and population centers. The other believes that although light pollution cannot be eliminated, it must be contained while still safeguarding the basic principles underlying public lighting. The UNI 10819:2021 standard works from this perspective.

On the one hand, the safety aspects and social phenomena associated with the lighting and night-time enhancement of built-up areas must be safeguarded. Still, on the other hand, it is not acceptable to have adverse biological effects and that we can no longer see the stars. One of the options that can be tried out on an experimental basis is lighting that varies during the night according to the needs of safety and usability of public spaces, with the added benefit of energy savings (Mclaughlin, 2018).

Italian national legislation is silent on light pollution, but many regions have started to legislate independently on the subject, sometimes with controversial results. In particular, the first version of the Lombardy regional law no. 199 of 31 May 2000, "Urgent measures on energy saving for outdoor lighting and combating light pollution," caused concern. In fact, this law makes technical assumptions considered inappropriate by experts. Three aspects, in particular, are contested, and which illustrate an often simplistic approach to the subject by people who are not experts in the field of lighting:

1. Requiring the use of luminaires with zero light emission above the horizontal plane. Unfortunately, this is only possible with luminaires with horizontally arranged flat glass; these luminaires have a narrower beam than cup-shaped luminaires, and therefore more must be used with higher electricity consumption. In addition, the more vertical lighting angle means that more light is reflected upwards from the ground.
2. Imposing the use of maximum efficiency sources. These were low-pressure sodium lamps in the street lighting, but they are large, and the flux is difficult to control; it would be more correct to speak of maximum efficiency luminaires.
3. Imposing the limitation of lighting during the various parts of the dark hours within limits is indispensable for safety. This does not consider all the cases in which lighting meets requirements other than the simple

safety of citizens, such as the enhancement of cultural sites and historical centers or the promotion of social activities during the dark hours, which for many months in winter begin as early as mid-afternoon or earlier in northern countries.

Apart from the technical objections, the Lombardy law of 2000 had two important objectives: to reduce light pollution and electricity consumption. Later, this law was replaced by the new Regional Law no. 31 of 5.10.2015 (Lombardia, 2015). This introduces new concepts such as a dedicated registry for monitoring and analyzing outdoor public lighting data and a strong push towards administrative simplification. In addition, the Municipal Lighting Master Plan (PRIC) has been replaced by the Outdoor Lighting Analysis Document (DAIE). The DAIE should enable the monitoring of the state of the installations and, based on the information contained therein, it will be possible to evaluate the opportunities and the modalities of efficiency improvement, upgrading, and acquisition of the installations. In addition, the new law promotes the use of materials and technologies that enable the provision of services that are complementary to public lightings, such as video surveillance, Wi-Fi connections, and traffic light management, with a view to the smart city. Thanks to the information collected and the interconnection between services, the law aims to reduce the risk of light pollution. Municipalities are tasked with managing the supervisory and control function regarding outdoor public lighting, monitoring violations, and applying sanctions.

The fact remains that in the absence of national law, the situation in Italy is patchy, with different rules in the various regions and autonomous provinces. Whereas in France and other European countries, there are laws and regulations at the national level. Outside the EU, there are also relevant examples such as the Chilean law 34/2012 to protect the night sky, as Chile is home to the world's most important telescopes, located in the Andes.

4.4 Lighting sustainability

Artificial lighting affects the environment, the biosphere, and the geosphere in three main ways:

1. The already mentioned problem of light pollution.
2. The consumption of electricity, the production of which leads to the destruction of non-renewable resources and pollution.
3. The environmental impact of lamp production and disposal.

Since the referendums on nuclear energy, following the catastrophic incidents in the power plants of Chernobyl in 1986 and Fukushima in 2011, electricity in Italy has been obtained mainly by thermal means through the consumption of fossil fuels, with the result that it costs 30% to 40% more than in the rest of Europe. Italy imports up to 13% of it from Switzerland, France, and other countries using nuclear power plants. Using hydrocarbons in thermal power stations also causes air pollution from sulfur dioxide, nitrogen oxides, benzene, particulates, and dust. According to the "Kyoto" protocol (UNFCCC, 1997), for reducing greenhouse gases, Europe, in the period 2005 to 2020, should have reduced emissions into the atmosphere by 8%, which in Italy is 6.5%. On the other hand, assuming average economic growth of close to 2% over the period, emissions increased by 12% instead of decreasing by 6.5%. Italy is also poor in fossil fuels and is therefore forced to import them, with the result that our economy is strongly influenced by changes in oil and gas prices.

This picture shows how valuable electricity is, although, according to ENEL sources, lighting consumes less than 7% of the electricity produced in Italy. This raises the question of whether it is really worthwhile tackling energy consumption in the lighting sector. The answer is still yes! And for several reasons. First of all, it is logically and ethically correct that all sectors contribute their share to reducing consumption and pollution. In addition, the need for public lighting is growing steadily, and this policy of intervention in general lighting should not be nipped in the bud by fears of increased energy consumption. For both the environment and the economy, a further important aspect is found in the range of activities related to the production and installation of new energy-efficient lighting systems contributing to the global economy as we emerge from a protracted economic crisis exacerbated by the Covid-19 pandemic.

A lighting designer can achieve excellent results in terms of energy savings by working on many aspects that go far beyond the simple use of energy-efficient light sources:

- Correct selection and sizing of lighting parameters in design. For most lighting applications, it is absolutely ineffectual to illuminate more than necessary or where it is not needed. To achieve these objectives, a decisive contribution is made by the new IT tools to support the design process (Carter, 1981; Krupiński, 2020).
- Maximum use of natural lighting in conjunction with artificial lighting in interiors (Borile *et al.*, 2017). This implies the analysis and the intervention of the lighting designer also on the architectural and

urbanistic aspects, in perspective already discussed in paragraph 2.6, which listed the levels of intervention of the lighting designer on the building project.

- The automatic programming, also based on environmental detection parameters, of even partial switch-on of indoor (Tan *et al.*, 2018) and outdoor lighting systems (Mclaughlin, 2018). This activity also depends on the correct use and programming of IT control systems.
- Optimum operation of lighting installations. I.e., proper scheduling of maintenance, cleaning, lamp replacement, wall painting, checking and calibrating automatic devices, and, in general, all activities contribute to keeping the lighting system in good working order (Perry, 1999; Tetri *et al.*, 2017).
- Use new light sources and devices with high efficiency, high durability, low power consumption, and small size. These include the wave of new LED lighting products for indoor and outdoor use that have appeared in recent years, together with electronic devices for power supply and intelligent lighting control (Siniscalco, 2021). Reducing the size of LED light sources has also been of paramount importance as it enables the design and production of luminaires that better control the distribution of light flow.

When it comes to the pure efficiency of the light source, low-pressure sodium lamps have long been the most efficient artificial light sources (Jack, 1978). They were invented in 1932, but they have been further improved through new technological processes and electronic power supplies in recent years. They are so efficient that they can produce up to 200 lumens of luminous flux per Watt of absorbed power (Sprengers, Campbell and Kostlin, 1985); this is because the emission is nearly monochromatic, concentrated almost entirely at a wavelength close to 600 nm, i.e., in the area of the electromagnetic spectrum where human beings are most sensitive to light radiation; for this very reason, however, monochromatic lighting of this type involves almost no perception of colors. Therefore, these lamps have been used in lighting for vehicular and industrial traffic, where good color perception was not required. In addition, they are generally large in size, making it challenging to design luminaires that control the distribution of luminous flux. LEDs have overtaken them in terms of efficiency and color rendering (Huang *et al.*, 2020).

In addition to efficiency and durability, LEDs also outperform other light sources because of their control flexibility (Protzman and Houser, 2006). They can be dimmed, have an instantaneous switch-on (unlike discharge lamps), and can be switched on and off countless times without affecting their service life (Malik, Ray and Mazumdar, 2020).

The correct positioning and choice of luminaires is the core activity of the lighting project (CIE, 2019; CEN, 2021). In addition to the aspects already dealt with in this text concerning the methodological approach based on IT tools and compliance with the listed standards, for which reference should be made to the specific manuals, three general aspects can be mentioned that may influence a conservative and correct use of electrical energy: the proper distribution of lighting levels according to the intended visual clarity (Vrabel, Bernecker and Mistrick, 1998) and performances (Vrabel, Bernecker and Mistrick, 1995), the choice of favoring a significant ratio of direct lighting, as long as it is comfortable, over indirect lighting, characterized by poorer efficiency (Fostervold and Nersveen, 2008), and the use of high-efficiency luminaires capable of conveying the light flow only where required and to the extent necessary (Cuttle, 2020).

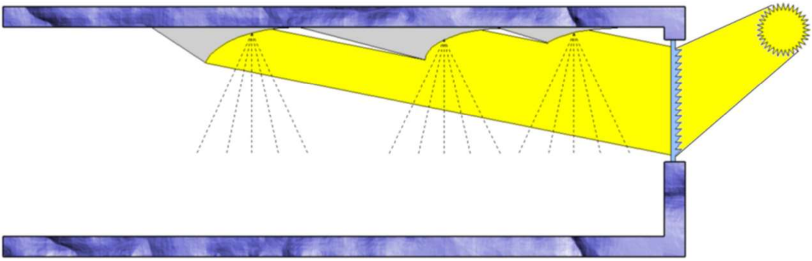


Figure 4.3 – Operation diagram of a system consisting of a refractor with double-glazed window that deflects the light towards the ceiling where appropriate reflectors distribute it inside.

For all workplaces and residential environments, the method that may appear to be the most straightforward and economical way to reduce energy consumption is the use of daylight (Borile *et al.*, 2017; Turan *et al.*, 2020). Daylight has positive effects on office workers (Borisuit *et al.*, 2015); however, it has several limitations: it is difficult to control, can easily cause glare, and in summer causes overheating; it depends on meteorological and spatial factors; it also depends on the architecture, urbanization, and the orientation of spaces concerning the cardinal points (Wienold *et al.*, 2019). For years, experiments have been carried out for the correct and effective control of solar illumination (Littlefair, 1990). These include light pipes and the introduction of dioptric plates inserted into the windows double glazing, which reflect sunlight towards the ceiling of the room where, in addition, suitably shaped baffle plates can be provided for the distribution of light in the room. Obviously, these systems must be supplemented by devices that automatically adjust the artificial lighting according to the illuminance levels in the various areas of the room detected by sensors (Caicedo, Li and Pandharipande, 2017; Tan *et al.*, 2018). Unfortunately, these hybrid lighting systems are not yet widespread and should be encouraged by legislative and regulatory measures.

Figure 4.4 – Solar powered street lamps.

Sunlight can be used for direct lighting during daylight hours and stored in electrical energy for use at night. One of the first historical examples of this type of technology was its application in the province of Brindisi for a network of 2300 photovoltaic street lights to illuminate long stretches of the local road network. The street lights used were capable of providing a luminous flux of 3500lm, powered by two 70W photovoltaic cell systems for the conversion of sunlight into electrical energy that is stored in two 12V lead batteries, managed by a microprocessor charge controller with a programmable clock. The street light switches on automatically at dusk. Still, after 6 hours of operation, the microprocessor checks the actual charging state of the batteries and disconnects the sodium lamp in the event of insufficient charge. The microprocessor controller solves the problems that affect most lighting systems of this type, which tend to discharge the batteries entirely during the night, damaging them and impairing the functionality of the lighting system. If the battery still has a sufficient charge after the first six hours of lighting, lighting is continued until dawn. This feature ensures that the lamp is switched on during peak traffic hours, even during winter periods with reduced energy storage due to prolonged bad weather, except that it is switched on until dawn as soon as the bad weather ceases.

Another crucial aspect of this type of installation is the independence from a power supply network and associated wiring. In fact, thanks to their ability to recharge daily, the lights can easily be placed even in extremely isolated and inaccessible places where there is no electricity distribution. However, if there is a mains supply, this can be used to replace the power supply of the batteries when they run down.

Efficiency and color rendering of light sources		
Source type	**Efficiency** [lm/W]	**CIE color rendering index**
Incandescent	8 - 15	100
Halogen	17 - 25	100
High pressure mercury	40 - 60	50 - 40
Compact fluorescent	50 - 80	85
Metal halides	60 - 80	90
Linear fluorescent	70 - 96	85 - 75
White LED	50 - 150	95 - 70
Low pressure sodium	140 - 180	0

Figure 4.5 – The light sources' efficiency and CIE color rendering index are inversely proportional. The LEDs have elevated both of these parameters.

Concerning high-efficiency light sources, it can be noted that their use is not yet applicable to all lighting needs. Unfortunately, in general, the higher the efficiency of a light source, the lower the color rendering, i.e., the ability to illuminate in such a way as to enable a correct perception of colors by the human visual system. CIE recommends using high color rendering sources between 90 and 100 for perceptual well-being for residential applications and, in general, for all meeting and entertainment environments (Boyce, 2014; CIE, 2017).

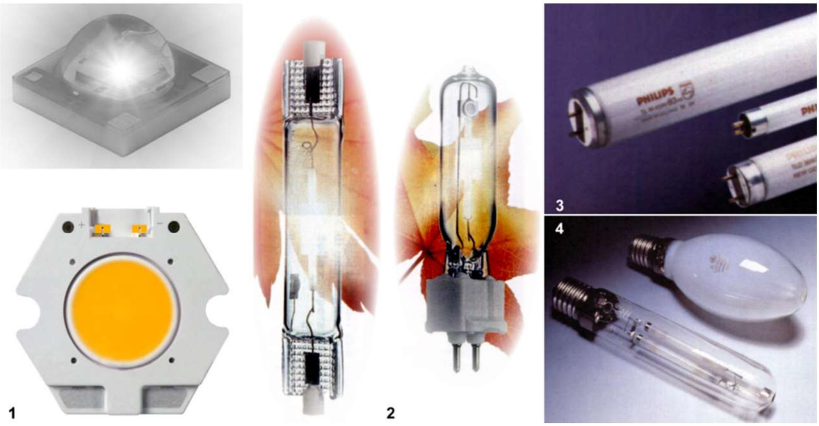


Figure 4.6 – High efficiency light sources. 1: LED. 2: Metal halide lamps with ceramic burner. 3: Linear fluorescent lamps. 4: Sodium lamps for outdoors..

Linear fluorescent lamps have been used in workplaces for decades, as they combine high efficiency with good color properties. In the last thirty years, technological advances have led to the continuous improvement of compact fluorescent lamps in terms of miniaturization and improved color properties, making them a viable and efficient alternative to incandescent lamps, even in interior lighting. Moreover, since 2009, the European Directive 2005/32/EC, also known as Eco-Design EUP, has progressively banned incandescent lamps, various types of halogen lamps, and, in the future, compact fluorescent lamps from production. Finally, LED sources have almost completely replaced the others thanks to falling prices.

Initially, the main obstacle to the broader use of LED lamps was the purchase price, which could be five to ten times higher than that of the classic incandescent or compact fluorescent bulb (Rea, 2010). This is in addition to a different appearance that has now been restored to the iconic status of the classic incandescent light bulb (Lin, 2015).

In the past, higher efficiency lamps were used where a good color assessment was not required, e.g., low or high-pressure sodium lamps were used in street lighting or for surveillance purposes. Other lamp types, such as metal halide lamps, offer a good compromise between efficiency and color rendering for applications such as sports facilities and production plants. Still, even these sources are losing ground to the LED wave innovation.

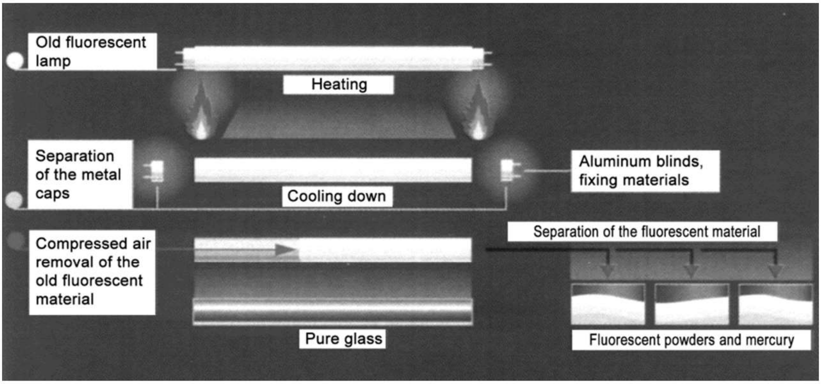


Figure 4.7 – The process that ensures the recycling of fluorescent powders, mercury, glass and all materials used in the production of fluorescent lamps.

Another aspect of environmental impact concerns the production and disposal of artificial lighting sources. The production aspects obviously do not involve the lighting designer except in his ability to favor ecological products. However, as far as manufacturing companies are concerned, ISO 14000 standard has long since outlined the environmental management system and the tools and procedures for introducing the ecological aspect into company management (ISO, 2015). However, this is a cross-cutting standard, i.e., applicable to all sectors. Italian legislation addressed waste disposal issues with Legislative Decree no. 22/1997 (Ronchi Decree), later repealed and replaced by Legislative Decree no. 152/2006 (Environmental Unified Code), for hazardous waste containing mercury. While LEDs are electronic devices and fall under the WEEE (waste electrical and electronic equipment) type of waste. Their end-of-life is regulated by European Directive 2012/19/EU, implemented in Italy by Legislative Decree no. 49 of 14 March 2014. These electronic products should be recovered separately because, even in small quantities, they contain valuable and/or polluting materials such as iron, steel, copper, aluminum, lead, mercury, silver, gold, and glass.

Despite the widespread use of LEDs, the focus of the lighting industry today is still on fluorescent lamps. Still today, these account for most sources installed in public interiors because of their efficiency and cost-effectiveness (Tähkämö *et al.*, 2014). Thanks to well-established production processes and new recycling methods, based on developing a network of collection sites for used lamps, companies have long since made the installer sector aware of the need to dispose of highly polluting fluorescent lamps (Bruni, 1999). The various technological factors that allow the latest fluorescent lamps to be identified as recyclable and environmentally friendly include:

- The decrease in the amount of mercury from 15 thousandths of a gram to 3 thousandths of a gram.
- The use of glass absorbs less mercury and is thus able to limit the decay of the luminous flux over the life of the lamp.
- The use of new phosphorescent powders that last longer and can be recovered and regenerated.
- The use of new high-frequency electronic ballasts can double the lamps' average life.

These aspects have also taken on a promotional value that is publicized through the green insert in the lamp socket as a symbol of environmental certification.

4.5 Lighting design methods and objectives

Lighting Design has the task to prefigure the whole and detail of the elements, structures, and actions suitable for the implementation of the lighting systems, respecting the legislative, regulatory, architectural, and functional constraints, compatibly with the objectives formulated by the customer. Since artificial lighting involves a system installed in an existing or planned site, the latter is obviously the starting point of the design process.

The project starts with a careful survey and analysis of the site to be illuminated. If the site already exists, the activity will be mainly aimed at studying and analyzing its current state. If the site does not exist, the analysis will focus on the building blueprint unless the lighting designer, who also has expertise in the field of natural light, is called upon to provide his opinions on the building project itself to make better use of daylight. The primary external constraints that will influence the design activity are defined in this phase. For this reason, the survey and analysis activity must be careful and focused on the features of the considered site. The survey and analysis work can be divided into the following aspects:

- Dimensions, geometry, and architectural/aesthetic aspects of interiors, exteriors, or parts to be lit.
- Daylighting at the site and related parameters, such as geographical location, orientation, and the presence of other neighboring structures that may affect sunlight and skylight.
- Types of human activities taking place on the site with particular attention to required visual tasks.
- Communication aspects related to the site to be illuminated.
- Research the laws and regulations concerning the type of lighting intervention according to the visual tasks involved.
- Types of materials and levels of reflection present or envisaged for the site.
- The situation of any pre-existing lighting and electrical installations.
- Environmental parameters such as humidity or the presence of dust can affect luminaires' operativity.

IT can offer many useful tools for organizing the work in the survey phase. In fact, they enable easy storage and cataloging of various types of data, from dimensions to descriptive data of the multiple entities considered, as well as facilitating the management and analysis of drawings with CAD and/or BIM support software of the building project or pre-existing structure. Another necessary support comes from researching and viewing online databases for relevant legislation and regulations and the communication between the customer and the designer concerning the project's development. In the third millennium Covid19 era, it is not unusual for the customer and the designer to be in different countries, thousands of kilometers apart, and manage their contacts by videoconference and sharing design material via Cloud services (Comacchio, 2021).

Once the survey and analysis of the site have been completed, the following step is to define the objectives. The objectives induced by the customer, those deriving from the constraints and the design method that the lighting designer imposes on himself. These are based on the functional, visual perceptive, and aesthetic goals the lighting system must pursue. In this sense, objectives can be divided into two main categories: functional/technical objectives and qualifying/aesthetic objectives.

The first category includes objectives aimed at ensuring the safety of all the lighting system components. Guaranteeing the efficiency and durability of the lighting service, facilitating its installation and maintenance, limiting energy consumption, and adapting the system to the changing performance required by the lighting needs of the site, i.e., all the exhibition design spaces that require continuous reconfiguration according to continuous changes in the layouts.

The second category includes objectives aimed at ensuring the communicative and perceptual aesthetic aspects of the lighting system, even when it is switched off. In addition to the aesthetics of the lighting, the aesthetics of the luminaires and the system, in general, must be considered, as they can also be visible during the day when they are switched off and must respect the architectural context in which they are installed. There are also objectives to meet the required visual tasks and promote efficient and comfortable vision. In this case, the term comfort is understood as visual comfort. Simply complying with the illuminance levels for visual tasks laid down in the regulations does not guarantee visual comfort, which does not depend solely on exact lighting levels provided on surfaces, but on the quality of lighting throughout the environment, which must be aimed at containing visual fatigue and disturbances caused by the effects of various types of glare: disturbing or disabling, direct or indirect. The introduction of the UGR index for interiors was also decisive in this context (Eble-Hankins and Waters, 2005; CIE, 2010). This does not assess comfort based only on the characteristics of the luminaires, as was the case with the old Sollner curves (Akashi and Kanaya, 1991), but the environment as a whole and the reflection factors and the colors of indoor materials or outdoor material (Casciani and Rossi, 2017). Also, the possible positions of users in the interior under consideration play a role in the assessment. Due to the large number of parameters involved, the UGR method can easily be calculated using a Lighting CAD (Son *et al.*, 2015). The lower the UGR, the more visually comfortable the environment is considered to be. The standard also establishes these ranges of recommended UGR values for typical indoors hosting various types of activities:

- 13÷16 Drawing, CAD, layout, and graphic processing.
- 16÷19 Test work, checks, controls.
- 19÷22 Writing and reading activities at the desk.
- 22÷25 Medium-duty industrial work.
- 25÷28 Heavy-duty industrial work.

In recent years, it has become apparent that the lighting design methodology is changing, shifting the focus more towards two factors that were previously not adequately considered. The human being is understood not only as a visual person but also as the environment with its materials and colors. In fact, the indoor lighting regulation (CEN, 2021) has less stringent constraints on design requirements than the previous regulation, thus leaving more room for interpretation to the lighting designer. However, it also introduces guidelines on the reflective-colorimetric characteristics of the materials planned by the interior design since they also influence visual comfort. Although the topic of joint lighting and color design indoor is still not very popular among designers, this topic will likely be further developed in the future. This could be when new IT tools will be available to support collaborative BIM design, which will make it possible to manage the actual characteristics of materials and light sources at the various levels of the project.

After defining the objectives, the phase of formulating possible solutions begins, which, while respecting internal and external constraints, leads to the achievement of the set goals. At this stage, designers, using their technical, scientific, cultural, and methodological skills, apply their experience and intuitive ability to quantitatively and qualitatively predict the final result in terms of lighting. In this sense, the difference between a classic licensed electrician and a lighting designer lies in the combination of scientific and technological preparation that the latter has acquired during his training in close relation to the cultural growth of inventiveness, artistic imagination, and the ability to explore the social and communicative aspects of light.

The solution(s) formulated is expressed using a graphic description, through technical drawings and text, of the lighting system, i.e., the drafting of the project that must include light sources, luminaires, accessories, power supply, and any structures aimed at managing natural light, complete with topological and editorial helpful information for their procurement and installation by qualified installers.

Historically, in this major phase of project development, the lighting designer has not had the representative and evaluative tools typical of prototyping available to other areas of industrial design. Many lighting designers base their methodology on a wealth of experience and intuition, which requires a long process of training and practical application. And it is precisely at this crucial stage of the project process that the innovation represented by the use of new IT calculation tools and virtual reality has simplified the lighting calculation methodology. We have moved from an approach based on highly approximate manual mathematical calculations to automatic calculation with a higher level of precision and detail. However, there is one fundamental point on which there should be no confusion: software enables verification of the design requirements, but it does not create the design and will never be able to replace the designer's creativity.

In addition to calculations for the quantitative and functional evaluation of lighting, the most innovative software tools also make it possible to obtain rendering images with a fair degree of photorealism and thus act as virtual perceptual prototypes to evaluate the qualitative and aesthetic aspects of lighting. By assessing the lighting design requirements, IT tools enable the analysis, verification, and comparison of the design solutions against the set objectives. In addition, the potential of IT tools to support the harvesting aspects of the lighting project should not be underestimated, as they provide extensive technical catalogs in electronic format for the retrieval of information on lamps, luminaires, and devices that can be used in the project.

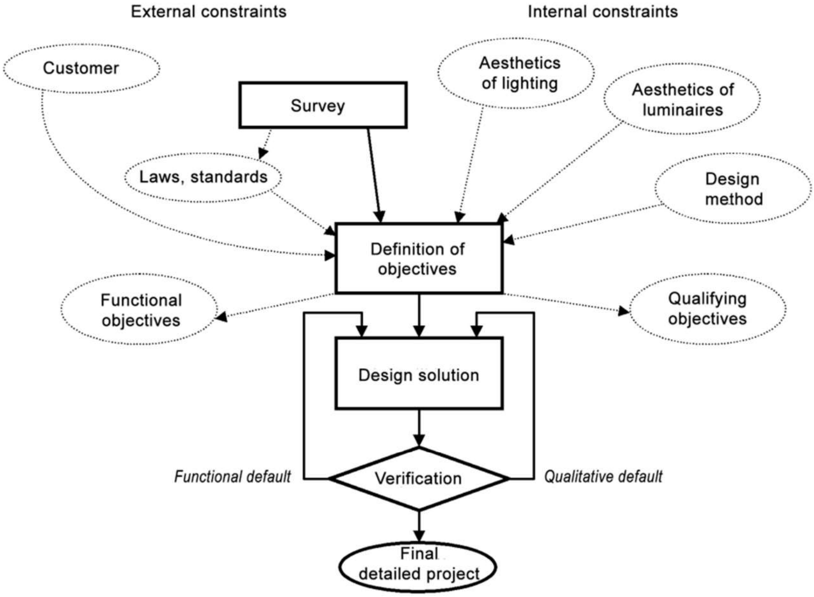


Figure 4.8 – Phases and constraints of the lighting design process.

Also, during the presentation of the project, the images, possibly supplemented by interactive multimedia animations, combined with the technical photometric representations, provide an essential communication tool that completes the technical elements for a comprehensive illustration of all aspects of the lighting design. However, attention must be paid to a critical part because presenting a rendering of a lighting project and confusing it with the project itself can be a severe mistake. The rendering must always be presented as information accompanying the project, making it clear to the client that it has a general representative value of the finished project, but with limits in its ability to faithfully represent the complexity of the real world in terms of colors and luminosity that can actually be perceived.

4.6 Conclusions

Until a few years ago, there was no uniform way of drawing up lighting plans, and it was common to see projects presented in very different ways. Fundamental help for the designer came from the standard "Light and lighting - Criteria for the preparation of the lighting design" (UNI, 2016). Without going into all the details of this standard, it is interesting to note that it opens with a statement on the importance of design: Lighting design is a compendium of art and science capable of illuminating the human environment. The standard lays down requirements for drawing up lighting plans in the following contexts:

- Indoor environments such as hospitals, hotels, offices, commercial, industrial and residential interiors, etc.
- Sports installations, indoors and outdoors.
- Road facilities (road, cycle or pedestrian), outdoor areas, such as parks, gardens, parking areas, etc.
- Architectural and monumental installations, indoors and outdoors.
- Tunnels and subways.

While lighting design is, in general, already regulated by existing Italian legislation (Decree 50 of 18/4/2016 Code of public contracts and the DPR 207 of 05/10/2010 on Decree 163 of 12/04/2006 and 270 of 10/12/2010 regarding public works), numbers are not the focus of the (UNI, 2016) standard and calculations are considered to be just one of many aspects that the lighting designer has to take into account. The standard emphasizes these aspects:

- Knowledge: on light, lighting, its instruments, its control, and management, which are today extremely complex.
- Light's impact on humans beyond vision is finally given new importance: circadian rhythms, mood, and attention span.
- The significance of the appearance that the lighting produced, and that the luminaires have in terms of aesthetics concerning the environment in which they are placed;

- The lighting of a place is a crucial element in ensuring safety and visual comfort.

There are four stages in the design process, as defined by this standard:

1. Feasibility Study. The feasibility study provides all the necessary and sufficient information for project decisions relating to technical and organizational feasibility through the analysis of the current state (survey), the evaluation of the customer's requirements and other specific needs, the identification of design alternatives, possible system geometries, optical and technical technologies, energy analysis, with an estimate of the costs of intervention, and economical estimate of savings and an estimate of the intervention times
2. Concept Design. The lighting concept defines the qualitative and functional characteristics of the work, the requirements to be met, and the services to be provided. This phase includes a multidisciplinary creative work for the search of original ideas, a report illustrating the preliminary project with the summary description of the current state and the identification of the main critical points; but also the analysis of the functional, aesthetic, formal, and economic objectives and the definition of the intervention perimeter. Sketches and mood boards are used for this purpose. In the technical report, an analysis of the functional and performance requirements of the project is made with lighting evaluations using preliminary calculations. An estimate of the costs of luminaires as well as control, management, and installation systems is also proposed.
3. Preliminary Design. The Preliminary Design is drawn up based on the indications of the approved Concept. It contains all the elements necessary to obtain the authorizations, such as the declaration of urban conformity or other equivalent acts mandatory for works in the public domain. It also develops the graphic and descriptive drawings and calculations to a level of definition such that there are no significant technical and cost differences in the subsequent detailed design.
4. Detailed Design. The Detailed Design ultimately defines every architectural, structural, and system-related engineering detail of the work to be carried out. This consists of a general report of the preliminary design: analysis of the current state; a detailed description of the project, analysis, and list of interventions; description of technical solutions and technological characteristics of the luminaires;

technical data sheets and photometric data of the products; energy analysis. This general report is also supported by specialist reports with lighting calculations of visual tasks, room surfaces, glare, and a maintenance plan. From a graphical standpoint, there is a representation of the current state and the planned intervention, with all the graphic drawings, blueprints, sections, and detailed diagrams necessary for the installation. Finally, there must also be a timetable for the works and the economic framework.

All these steps in the design process establish since inception that a lighting project is an essential factor that is still not adequately understood and applied today in many countries. Moreover, this process places the individual at the center of the design process. It makes the evaluation or comparison of several design hypotheses less complex, thus providing parameters for comparison both regarding the completeness of the documentation and compliance with the minimum levels of detail required by current legislation and regulations.

4.7 Conflict of interest declaration

The author declares that nothing has affected his objectivity or independence in the production of this chapter. Neither the author nor his immediate family member has any financial interest in the people, manufacturer or topics involved in this article. The author also declares that no conflict of interest, including financial, personal, or other relationship with other people and organizations, could inappropriately influence, or be perceived to influence, this work.

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