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PREFACE

A considerable amount of the energy used in lighting is consumed without contributing to good vision conditions. The basic reasons for wasting the energy used in lighting are:

- the great loss ratios in the phases from "producing light by electrical energy" to "obtaining good vision conditions";

- the enlargement of these loss ratios in every phase by multiplying by each other;

- The choice of wrong lighting strategies that amplify the energy use.

The aim of the European Performance of Buildings Directive 2002/91/EC is to provide an energy certificate, which indicates the energy consumption of a building. CEN was asked to deliver standards for measuring and calculating the energy consumption for heating, ventilation, cooling, domestic hot water, lighting, and the control system. In CEN TC 169 "Light and Lighting", WG 9 has delivered part 1 of the draft standard PrEN 15193-1 "Lighting energy estimation". The second part, currently in preparation, has to identify benchmarks for the energy consumption of lighting applications. The ratio of good vision conditions provided in a room to the consumed energy is becoming a common index for the assessment of the office lighting strategies.

In PrEN 15193-1 the LENI index is used:

$$LENI = \frac{W_{light}}{A} \qquad \left[\frac{kWh}{m^2 \, year} \right]$$

In this standard are given benchmark values for several applications. In this study has been developed an approach to determine the good vision efficiency in a room and are reported some examples of office room's calculations. It has been made a critical review about the benchmark values given in the PrEN 15193 for several applications. The aim is to point out if those values are eventually too high.

1. Fundamentals

1.1. From nature's light to artificial lighting

Light is life, the relationship between light and life cannot be stated more simply than that. Most of the information we receive about our surroundings is provided by our eyes. We live in a visual world. The eye is the most important sense organ in the human body, handling around 80% of all incoming information, light is the medium that makes visual perception possible. Insufficient light or darkness gives rise to a sense of insecurity. Artificial lighting during the hours of darkness makes us feel safe. So light not only enables us to see; it also affects our mood and sense of wellbeing. Lighting level and light color, modelling and switches from light to dark impact on momentary sensations and determine the rhythm or our lives. In sunlight, for instance, illuminance is about 100,000 lux. In the shade of a tree it is around 10,000 lux, while on a moonlit night it is 0.2 lux, and even less by starlight. People nowadays spend most of the day indoors – in illuminances between 50 and 500 lux. Light sets the rhythm of our biological clock but it needs to be relatively intense to have an effect on the circadian system (> 1000 lux), so for most of the time we live in "chronobiological darkness". The consequences are troubled sleep, lack of energy, irritability, even severe depression. As we said above, light is life. Good lighting is important for seeing the world around us. What we want to see needs to be illuminated. Good lighting also affects the way we feel, however, and thus helps shape our quality of life.

1.2. The physics of light: basics.

History has produced various theories that today strike us as comical but were seriously propounded in their time. For example, since no connection could be discerned between a flame and the object it rendered visible, it was at one time supposed that "visual rays" were projected by the eyes and reflected back by the object. Of course, if this theory were true, we would be able to see in the dark. In 1675, by observing the innermost of the four large moons of Jupiter discovered by Galileo, O. Römer was able to estimate the speed of light at 2.3×10^8 m/s. A more precise measurement was obtained using an experimental array devised by Léon Foucault: 2.98×10^8 m/s. The speed of light in empty space and in air is

generally rounded up to 3 x 108 m/s or 300,000 km/s. This means that light takes around 1.3 seconds to travel from the Moon to the Earth and about 81/3 minutes to reach the Earth from the Sun. Light takes 4.3 years to reach our planet from the fixed star Alpha in Centaurus, about 2,500,000 years from the Andromeda nebula and more than 5 billion years from the most distant spiral nebulae. Different theories of light enable us to describe observed regularities and effects. The corpuscular or particle theory of light, according to which units of energy (quanta) are propagated at the speed of light in a straight line from the light source, was proposed by Isaac Newton. The wave theory of light, which suggests that light moves in a similar way to sound, was put forward by Christiaan Huygens. For more than a hundred years, scientists could not agree which theory was correct. Today, both concepts are used to explain the properties of light: light is the visible part of electromagnetic radiation, which is made up of oscillating quanta of energy. It was Newton again who discovered that white light contains colors. When a narrow beam of light is directed onto a glass prism and the emerging rays are projected onto a white surface, the colored spectrum of light becomes visible. In a further experiment, Newton directed the colored rays onto a second prism, from which white light once again appeared. This was the proof that white sunlight is the sum of all the colors of the spectrum. In 1822, Augustin Fresnel succeeded in determining the wavelength of light and showing that each spectral color has a specific wavelength. His statement that "light brought to light creates darkness" sums up his realization that light rays of the same wavelength cancel each other out when brought together in corresponding phase positions. Max Planck expressed the quantum theory in the formula:

$$E = h \times v$$

<div align="right">Eq. 1-1</div>

The energy E of an energy quantum (of radiation) is proportional to its frequency v, multiplied by a constant h (Planck's quantum of action). The Earth's atmosphere allows visible, ultraviolet and infrared radiation to pass through in such a way that organic life is possible. Wavelengths are measured in nanometers (nm) $=10^{-9}$ m $= 10^{-7}$ cm. One nanometer is a ten-millionth of a centimeter. Light is the relatively narrow band of electromagnetic radiation to which the eye is sensitive. The light spectrum extends from 380 nm (violet) to 780 nm (red). Each wavelength has a distinct color appearance, and from short-wave violet through blue, green, green yellow, orange up to long wave red, the spectrum of sunlight exhibits a continuous sequence. Colored objects only

appear colored if their colors are present in the spectrum of the light source. This is the case, for example, with the sun, incandescent lamps and fluorescent lamps with very good color rendering properties. Above and below the visible band of the radiation spectrum lie the infrared (IR) and ultraviolet (UV) ranges. The IR range encompasses wavelengths from 780 nm to 1 nm and is not visible to the eye. Only where it encounters an object is the radiation absorbed and transformed into heat. Without this heat radiation from the sun, the Earth would be a frozen planet. Today, thanks to solar technology, IR radiation has become important both technologically and ecologically as an alternative energy source. For life on Earth, the right amount of radiation in the UV range is important. This radiation is classed according to its biological impact as follows:

- UV-A (315 to 380 nm), suntan, solaria;

- UV-B (280 to 315 nm), erythema (reddening of the skin), sunburn;

- UV-C (100 • to 280 nm), cell destruction, bactericidal lamps.

Despite the positive effects of ultraviolet radiation, UV-B for vitamin D synthesis, too much can caused damage. The ozone layer of the atmosphere protects us from harmful UV radiation, particularly from UV-C. If this layer becomes depleted (ozone gap), it can have negative consequences for life on Earth.

1.2.1.   The physiology of light: basics

The optical components of the eye can be compared to a photographic camera (Figure 1-2) The image-producing optics consists of the cornea, the lens and the intervening aqueous humor. Alteration of the focal length needed for accurate focusing on objects at varying distances is effected by an adjustment of the curvature of the refractive surfaces of the lens. With age, this accommodative capacity decreases, due to a hardening of the lens tissue. With its variable central opening, the pupil, the iris in front of the lens functions as an adjustable diaphragm and can regulate the incident luminous flux within a range of 1:16. At the same time, it improves the depth of field. The inner eye is filled with a clear, transparent mass, the vitreous humor.
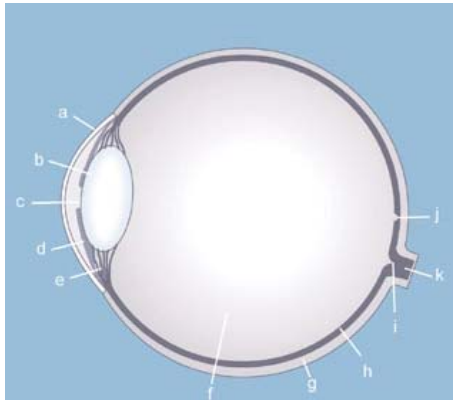
Figure 1-1 The eye's „components": a) cornea, b) lens, c) pupil, d) iris, e) suspensory ligaments/ciliary muscles, f) vitreous humor, g) sclera, h) retina, i) blind spot, k) optic nerve, l) fovea.

The retina (Figure 1-3) on the inner wall of the eye is the "projection screen". It is lined with some 130 million visual cells. Close to the optical axis of the eye there is a small depression, the fovea, in which the visual cells for day and color vision are concentrated. This is the region of maximum visual acuity.
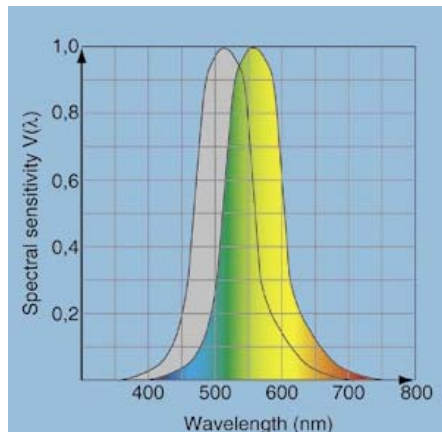
Figure 1-2 Curve of relative spectral sensitivity for day vision (cones) V(λ) and night vision (rods) V'(λ).

Depending on the level of brightness (luminance), two types of visual cell, cones and rods, are involved in the visual process. The 120 million rods are highly sensitive to brightness but relatively insensitive to color. They are therefore most active at low luminance levels (night vision); their maximum spectral sensitivity lies in the blue-green region at 507 nm. The 7 million or so cones are the more sensitive receptors for color. These take over at higher levels of luminance to provide day vision. Their maximum spectral sensitivity lies in the yellow-green

range at 555 nm (Figure 1-2). There are three types of cone, each with a different spectral sensitivity (red, green, blue), which combine to create an impression of color. This is the basis of color vision. The ability of the eye to adjust to higher or lower levels of luminance is termed adaptation.
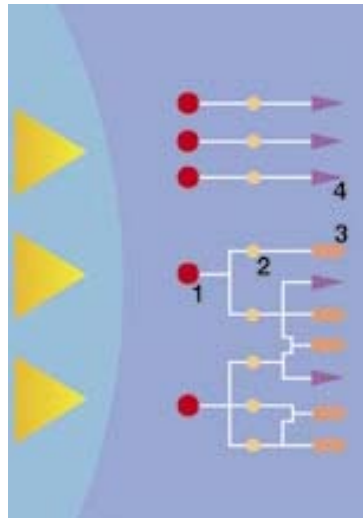
Figure 1-3 Schematic structure of the retina: 1) ganglion cells, 2) bipolar cells, 3) rods, 4) cones.

The adaptive capacity of the eye extends over a luminance ratio of 1:10 billion. The pupils control the luminous flux entering the eyes within a range of only 1:16, while the "parallel switching" of the ganglion cells enables the eye to adjust to the far wider range. The state of adaptation affects visual performance at any moment, so that the higher the level of lighting, the more visual performance will be improved and visual errors minimized. The adaptive process and hence adaptation time depend on the luminance at the beginning and end of any change in brightness. Dark adaptation takes longer than light adaptation. The eye needs about 30 minutes to adjust to darkness outdoors at night after the higher lighting level of a workroom. Only a few seconds are required, however, for adaptation to brighter conditions. Sensitivity to shapes and visual acuity are prerequisites for identification of details. Visual acuity depends not only on the state of adaptation but also on the resolving power of the retina and the quality of the optical image. Two points can just be perceived as separate when their images on the retina are such that the image of each point lies on its own cone with another "unstimulated" cone between them. Inadequate visual acuity (Figure 1-5) can be due to eye defects, such as short- or long-sightedness, insufficient

contrast, insufficient illuminance. Four minimum requirements need to be met to permit perception and identification:

- A minimum luminance is necessary to enable objects to be seen (adaptation luminance). Objects that can be identified in detail easily during the day become indistinct at twilight and are no longer perceptible in darkness.(Figure 1-4)

- For an object to be identified, there needs to be a difference between its brightness and the brightness of the immediate surroundings (minimum contrast). Usually this is simultaneously a color contrast and a luminance contrast.(Figure 1-6, Figure 1-7)

- Objects need to be of a minimum size.(Figure 1-8)

- Perception requires a minimum time. A bullet, for instance, moves much too fast. Wheels turning slowly can be made out in detail but become blurred when spinning at higher velocities.(Figure 1-9)

The challenge for lighting technology is to create good visual conditions by drawing on our knowledge of the physiological and optical properties of the eye.

Figure 1-4 Adaptation of the eye: On coming out of a bright room and entering a dark one, we at first see „nothing" – only after certain period of time do objects start to appear out off the darkness.

$$\text{Visus} = \frac{1}{\text{angle of vision in angular minutes}}$$

$$\text{Visus} = \frac{1}{0.5'} = 2$$

$$\text{Visus} = \frac{1}{1'} = 1$$
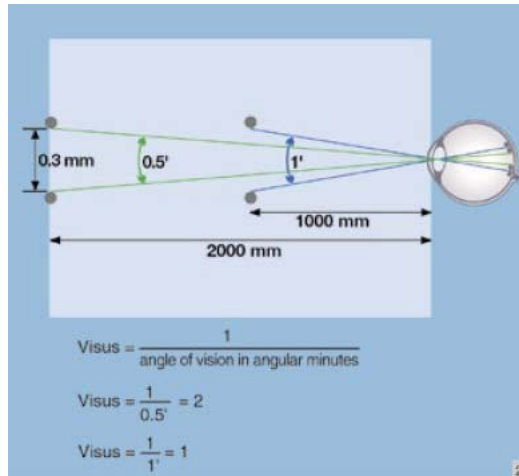
Figure 1-5 here two points 0.3 mm apart are identified from a distance of 2 m, visual acuity is 2. If we need to be 1 m from the visual object to make out the two points, visual acuity is 1.

Figure 1-6 Luminance contrast
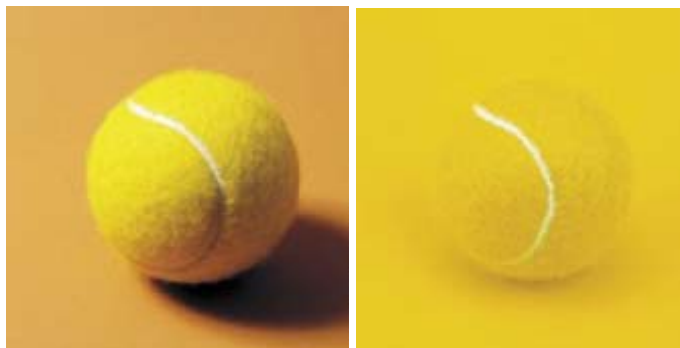
Figure 1-7 Color contrast

Figure 1-8 Minimum visibility size

Figure 1-9 Perception of an object in motion

1.3.　　The electromagnetic spectrum

Light is a form of energy. It passes from one body to another and can do so without the need for any substance in the intervening space. Such energy is termed radiation and it is said to be electromagnetic in character. The radiation thus has both an electric field and a magnetic field. Both of these fields vary sinusoidally and are mutually at right angles, as shown in Figure 1-10
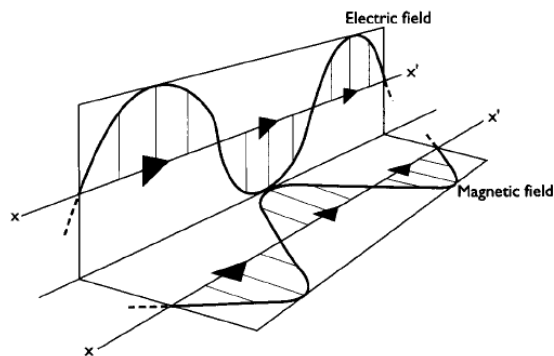
Figure 1-10 Electric field and magnetic field mutually at right angles. Electric field and magnetic field have same axis x-x' but are shown separately for clarity only.

Visible radiation is the term given to that radiation which is detectable by the eye. It occupies only a relatively narrow range of wavelengths within the whole of the electromagnetic spectrum. Figure 1-11 shows the electromagnetic spectrum with the visible spectrum shown in detail.
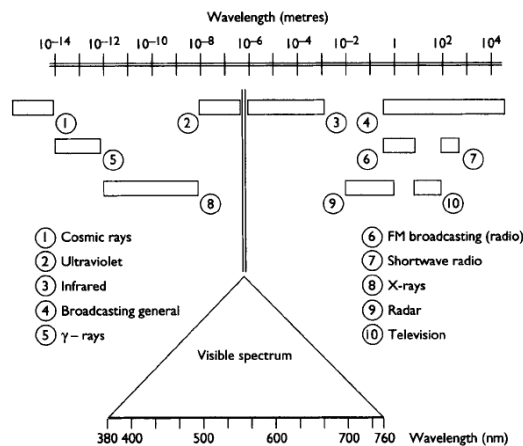
Figure 1-11 Electromagnetic spectrum I.
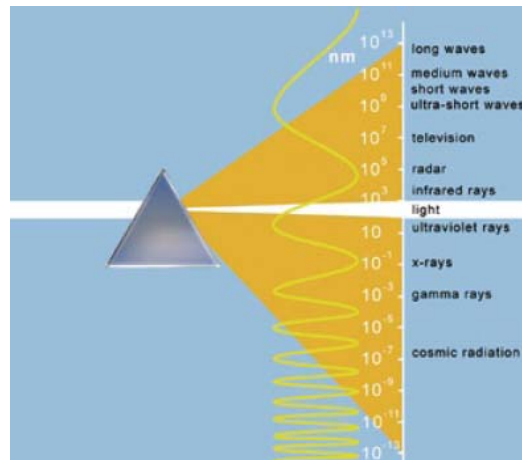
Figure 1-12 Electromagnetic spectrum II

1.3.1. Optical radiation

Electromagnetic radiation which lays in the wavelength range 100 nanometers to 1 millimeter is referred to as optical radiation. It follows that optical radiation covers visible radiation together with ultraviolet (W) and infrared (IR) radiation. Whilst the visible spectrum is essential for seeing, UV and IR radiation can have adverse effects on the body, including the skin and the eyes. All bodies emit optical radiation over a relatively wide wavelength range. For a black body, the peak emission of radiation occurs at a wavelength which is determined by Wien's law:

$$\lambda = \frac{2898}{T} \qquad\qquad 1\text{-}2$$

where A is the wavelength (in micrometers) and T is the absolute temperature on the Kelvin scale.

1.3.2. Ultraviolet and infrared radiation

At lower wavelengths than the visible spectrum the radiation becomes ultraviolet (UV), whereas at higher wavelengths than the visible spectrum the radiation becomes infrared IR. Both IR and UV radiation are sub-divided into three groups as shown in Tab. 1-1.

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Group	Ultraviolet	Infrared
A	315–400	780–1400
B	280–315	1400–3000
C	100–280	3000–1000000

All wavelengths are given in nanometres.

Tab. 1-1 Classification of UV and IR radiation

Ultraviolet radiation is usually produced either by the heating of a material to incandescence or alternatively by the excitation of a gas discharge. The major source of W radiation is the sun, which can be considered to be a huge incandescent mass. When produced by incandescence, W radiation is in the form of a continuous spectrum. An everyday example of the emission of ultraviolet radiation in industry is the electric arc produced in the welding process. The arc is established by the passage of an electric current across an air gap and between two metallic conductors or electrodes. The electrode tip, work piece and air gap are collectively heated until incandescence is reached. Analysis of the spectrum so produced will show that there is a continuum with discrete spectral lines superimposed. The characteristics of these lines are influenced by the properties of the materials from which the electrode and work piece are constructed and by the properties of the surrounding gases.

1.4.   Continuous and discontinuous radiation

When a solid object is heated to a sufficiently high level it reaches incandescence and the electrons will be violently agitated resulting in constant collision with other electrons. Some of the energy which results as a consequence of these collisions will be radiated from the hot body. Because of the closely-packed arrangement of the individual atoms in a solid body, the energy released will appear as a continuum characteristic of the temperature of the radiating body. The output is therefore radiation which is smoothly distributed over a relatively wide range of wavelengths. Some of the output wavelengths will be in the visible range but by far the greater proportion will appear in the infrared region as shown in Figure 2-13. A gas or vapor, when excited, behaves differently to a solid body. When excited, a gas or vapor will contain electrons which have been raised to a higher energy orbit around the nucleus. These electrons will very quickly return to their normal orbits and in so doing the energy they release is emitted as photons.

Such radiation is usually emitted at a sequence of one or more wavelengths producing a discontinuous spectral output.
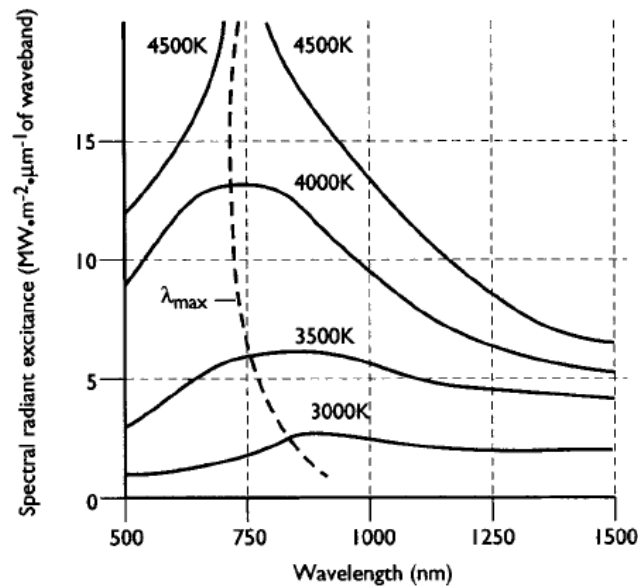
Figure 1-13 Black body radiation in accordance with Planck's law.

1.4.1. Spectral power distribution (SPD)

This is the term applied to the plot of variation in output from a body, typically a light source, with wavelength. The curves of Figure 1-13 are spectral power distributions (SPDs).

1.5. Black body radiation

A black body is one that exhibits the maximum amount of radiation theoretically, and completely absorbs all incident radiation which falls on it when the body is maintained at a uniform temperature. There are no such bodies in reality although many bodies closely approximate to it. If a body is held at a uniform temperature it will radiate thermal radiation in accordance with Planck's law. Figure 1-13 shows the relative energy radiated at various wavelengths by a black body at different temperatures. This shows that the wavelength of maximum radiation decreases as the temperature increases. In addition, Wien showed that the product of wavelength of maximum radiation and absolute temperature is a constant.
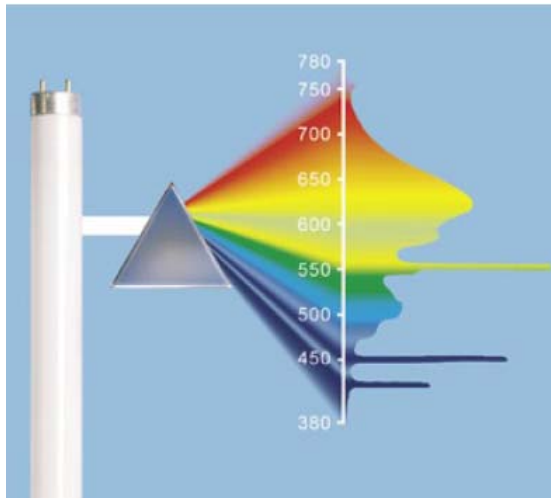
Figure 1-14 Spectral distribution of a fluorescent lamp

1.6. Wavelength, frequency and the velocity of propagation of light

Light travels sinusoidally in waves as discussed in Section 1.3. A relationship exists between the length of the wave, its frequency and the velocity of propagation such that:

$$\frac{Velocity}{(m/s)} = \frac{Frequency}{(Hz)} \times \frac{Wavelength}{m}$$

1-3

1.7. Radiant flux and radiant efficiency

Radiant flux is the term given to the total power of electromagnetic radiation (measured in watts) emitted or received. The value may include both visible and invisible components, the visible component being referred to as luminous. The radiant efficiency of a radiating source is the term given to the ratio:

$$Radiant \quad efficiency = \frac{radiant \quad flux \quad emitted}{power \quad consumed} \times 100\%$$

1-4

Measurement of radiant flux is usually achieved by means of power sensing transducers e.g. thermopiles. Measurement of radiant flux is termed radiometry.

1.8. Luminous flux, luminous efficacy and luminous efficiency

1.8.1. Luminous flux Φ

Radiant flux which contains those wavelengths which are detectable by the human eye is said to have a corresponding value of luminous flux. The unit of luminous flux is termed the lumen. Ratings are found in lamp manufacturers'lists. The luminous flux of a 100 W incandescent lamp is around 1380 lm, the one of a 20 W compact fluorescent lamp with built-in electronic ballast around 1200 lm.

1.8.2. Luminous efficacy

Theoretically the maximum attainable luminous output for unit power input is approximately 683 lumens at a wavelength of 555 nm. Thus the luminous efficacy is said to be 683 lumens per watt. Luminous efficacy is expressed in lumens per watt (lm/W). For example, an incandescent lamp produces approx. 14 lm/W, a 20 W compact fluorescent lamp with built-in EB approx. 60 lm/W.

1.8.3. Luminous efficiency

The term luminous efficiency is applied to the ratio of luminous efficacy at any given wavelength to the maximum possible luminous efficacy (683 lumens per watt). Luminous flux is usually measured by a light meter, containing a suitably-corrected photoelectric cell. Measurement of luminous flux is referred to as photometry.

1.9. Luminous intensity I

Luminous intensity is a measure of the luminous flux per steradian emitted in a given direction, and is measured in candela (cd). The candela is often referred to as the luminous intensity, in a specified direction, of a light source which emits monochromatic radiation of a frequency 540×10^{12} Hz, and which has a radiant intensity in the same direction of (1/683) Watts per steradian. The way the luminous intensity of reflector lamps and luminaires is distributed is indicated by curves on a graph. These are known as intensity distribution curves (IDCs). To permit comparison between different luminaires, IDCs usually show 1000 lm (= 1 klm) curves. This is indicated in the IDC by the reference cd/klm. The form of presentation is normally a polar diagram, although x-y graphs are often found for floodlights.

1.10. Light output ratio η_{LB}

It is the ratio of the radiant luminous flux of a luminaire to the luminous flux of the fitted lamp. It is measured in controlled operating conditions.

1.11. Glare

It is annoying. It can be caused directly by luminaires or indirectly by reflective surfaces. Glare depends on the luminance and size of the light source, its position in relation to the observer and the brightness of the surroundings and background. Glare should be minimized by taking care over luminaire arrangement and shielding, and taking account of reflectance when choosing colors and surface structures for walls, ceiling and floor. Glare cannot be avoided altogether. It is especially important to avoid direct glare in street lighting as this affects road safety. Where VDU workplaces are present, special precautions must be taken to avoid reflected glare.

1.12. Reflectance ρ

It indicates the percentage of luminous flux reflected by a surface. It is an important factor for calculating interior lighting. Dark surfaces call for high illuminance, lighter surfaces require a lower illuminance level to create the same impression of brightness. In street lighting, the three dimensional distribution of the reflected light caused by directional reflectance (e.g. of a worn road surface) is an important planning factor.

1.13. Illuminance, luminance and luminosity

Two useful examples illustrate the difference in the two parameters. Consider a petrol station forecourt as shown in Figure 1-15. The advertising sign at the entrance to the petrol station is typically lit internally by tubular fluorescent lamps. The effect is to produce a double-sided sign whose surface appears uniformly lit. The purpose of this illuminated sign is to attract the motorist to the petrol station and further to advice the motorist of the prices of the goods on offer and also of any other facilities provided. The advertising sign is not designed specifically to illuminate the area adjacent to the fuel pumps on the station forecourt. When considering the effectiveness of the advertising sign it is important to be aware of the luminance of the sign, i.e. the intensity of light emanating from the sign per unit area of the sign.
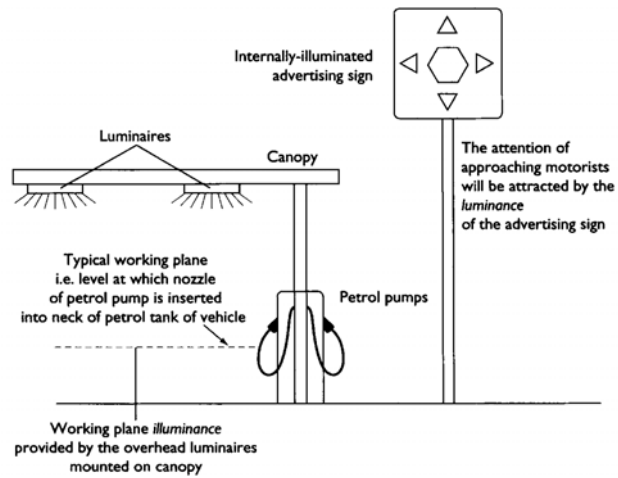
Figure 1-15 Petrol station forecourt.

1.13.1. Luminance L

It indicates the brightness of an illuminated or luminous surface as perceived by the human eye. Luminance (symbol L) is the luminous intensity emitted by a light source per unit area. (cd/m²). For lamps, the "handier" unit of measurement cd/cm² is used. Luminance describes the physiological effect of light on the eye; in exterior lighting it is an important value for planning. With fully diffuse reflecting surfaces – of the kind often found in interiors – luminance in cd/m² can be calculated from the illuminance E in lux and the reflectance ρ:

$$L = \rho \times \frac{E}{\pi}$$

1-5

1.13.2. Illuminance E

Illuminance (symbol E) is the term given to the quantity of luminous flux falling on unit area of a surface. It is measured in lux (lx), which is equivalent to lumens per square meter, on horizontal and vertical planes.

1.13.3. Maintained illuminance E_m and luminance Lm

They depend on the visual task to be performed. Illuminance values for interior lighting are set out in the harmonized European standard DIN EN 12464-1. Illuminance and luminance values for street lighting are stipulated in DIN EN 13201-2. Sports facility lighting is covered by another harmonized European

standard, DIN EN 2193. Maintained values re the values below which average values on a specified surface are not allowed to fall.

1.13.4. Luminosity

Luminosity is often referred to as 'apparent brightness' and describes the sensation experienced by an observer who is subjected to the stimulus of luminance. Consider the example of an observer who is looking at the headlights of a car. The luminance of the headlights will be the same whether the headlights are viewed during bright daylight or in darkness. It will be evident however that the headlights appear much brighter during darkness than they do in bright daylight. In such cases the headlights have a different luminosity value in the darkness to that occurring in bright daylight.
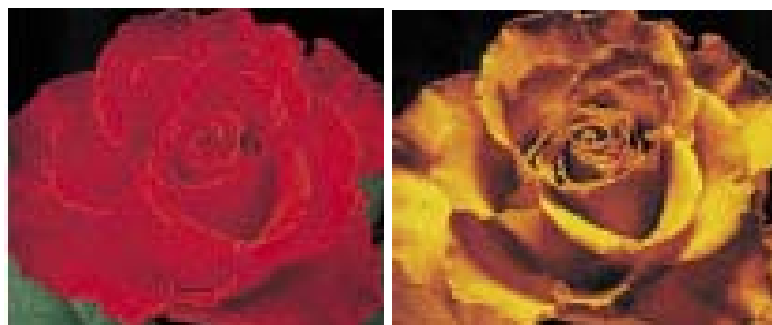
Figure 1-16 Compared with its appearance in daylight, a red rose looks unnatural under the monochromatic yellow light of a low-pressure sodium vapor lamp. This is because the spectrum of such light contains no red, blue or green, so those colors are not rendered.

1.14. Uniformity

Uniformity illuminance or luminance is another quality feature. It is expressed as the ratio of minimum to mean illuminance ($g_1 = E_{min} / E$) or, in street lighting, as the ratio of minimum to mean luminance ($U_0 = L_{min} / L$). In certain applications, the ratio of minimum to maximum illuminance $g_2 = E_{min} / E_{max}$ is important.

1.15. Maintenance factor:

With increasing length of service, illuminance decreases as a result of ageing and soiling of lamps, luminaires and room surfaces. Under the harmonized European standards, designer and operator need to agree and record maintenance factors

defining the illuminance and luminance required on installation to ensure the values which need to be maintained. Where this is not possible, a maintenance factor of 0.67 is recommended for interiors subject to normal ageing and soiling; this may drop as low as 0.5 for rooms subject to special soiling. For "sports facility lighting", DIN EN 12193 stipulates a maintenance factor of 0.8. Maintained value and maintenance factor define the value required on installation: maintained value = value on installation x maintenance factor.

$$ma\operatorname{int}ained \quad value = installed \quad value \times ma\operatorname{int}enance \quad factor$$

1.16. Quality features in lighting

Just as the nature of occupational and recreational activities differs – e.g. reading a book, assembling miniature electronic components, executing technical drawings, running color checks in a printing works, etc. – so too do the requirements presented by visual tasks. And those requirements define the quality criteria a lighting system needs to meet. Careful planning and execution are prerequisites for good quality artificial lighting.

This is what specific "quality features" determine:

- lighting level – brightness,

- glare limitation –vision undisturbed by either direct or indirect glare,

- harmonious distribution of brightness – an even balance of luminance,

- light color – the color appearance of lamps, and in combination with color rendering – correct recognition and differentiation of colors and room ambience,

- direction of light and modelling – identification of three-dimensional form and surface textures.
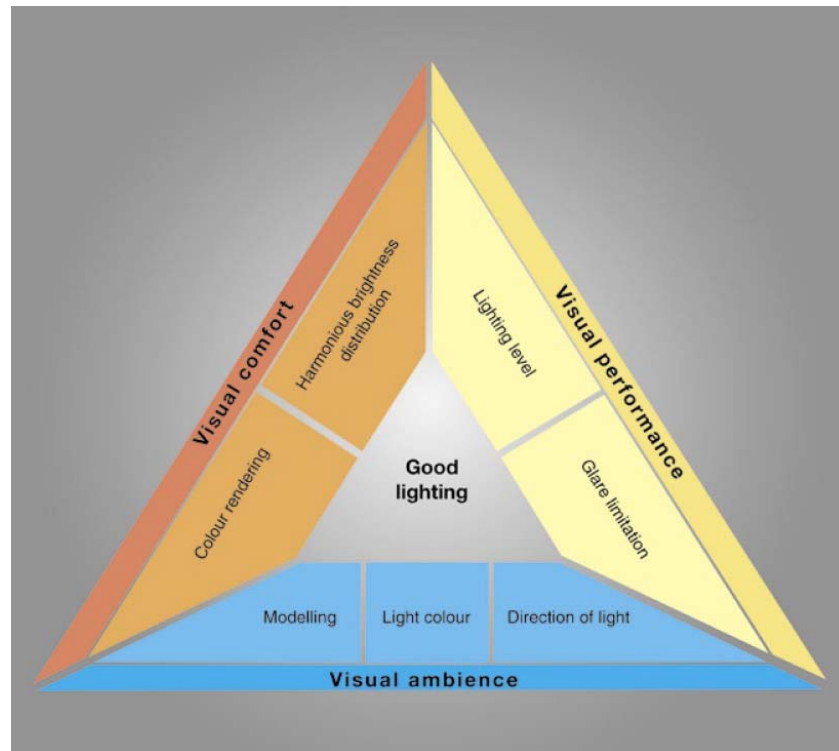
Figure 1-17

Depending on the use and appearance of a room, these "quality features" (Figure 1-17) can be given different weightings. The emphasis may be on:

- visual performance, which is affected by lighting level and glare limitation,

- visual comfort, which is affected by color rendering and harmonious brightness distribution,

- visual ambience, which is affected by light color, direction of light and modelling.

2. Light sources

2.1. A brief history of light sources

The earliest man-made light sources were fire, torches, and candles. Ancient Egyptians used hollowed-out stones filled with fat, with plant fibers as wicks. These were the first candles, and they date back to about 3000 BC. In the Middle Ages, candles were made of tallow, a type of animal fat; later they were made of beeswax or paraffin. Modern candles can still be thought of as a type of fat lamp, but their use today is almost entirely decorative. Ancient Greeks and Romans made lamps from bronze or pottery that burned olive oil or other vegetable oils in their spouts. Many oil lamps appeared during the Middle Ages, when reflectors were added to their designs. Early American colonists used fish oil and whale oil in their Betty lamps. Many improvements were made in the design and fabrication of these lamps over the years, but none produced light efficiently until 1784, when a Swiss chemist named Argand invented a lamp that used a hollow wick to allow air to reach the flame, resulting in a bright light. Later, a glass cylinder was added to the Argand lamp allowing the flame to burn better. With the birth of the petroleum industry, kerosene became a widely used fuel in these lamps. In the 1800s gas lamps became popular as street lights, originating in London, England. The gas lamp had no wick, but its chief drawback was an open flame that produced considerable flicker. The electric lamp replaced gas lamps in the late 1800s and early 1900s. The first electric lamp was the carbon-arc lamp, demonstrated in 1801 by Sir Humphrey Davy, but electric lights became popular only after the incandescent lamp was developed independently by Sir Joseph Swan in England and Thomas Edison in the United States. The latter patented his invention in 1879 and subsequently made the invention the commercial success that it is today. Figure 2-1 illustrates the history of different light sources.
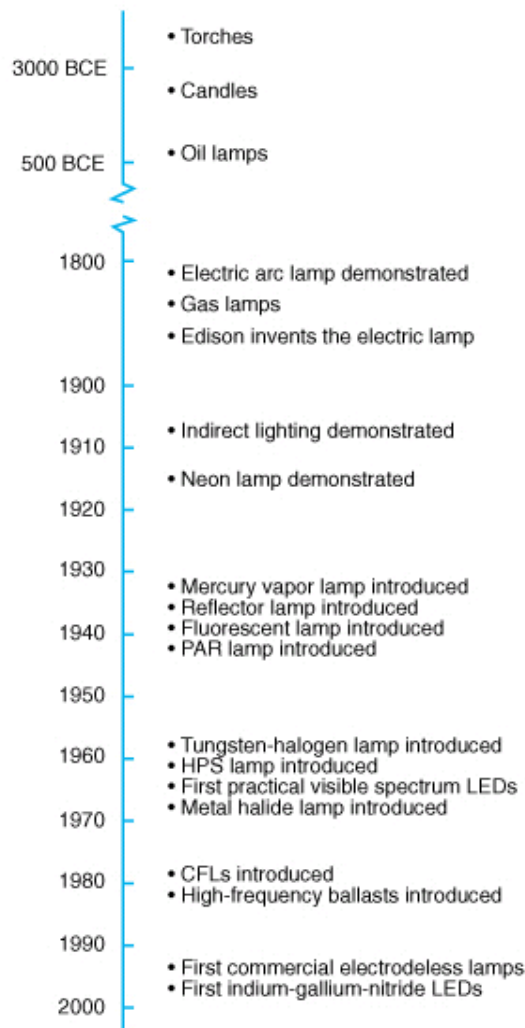
Figure 2-1 Time line of light sources

This century has seen a huge increase in the number of available light sources in the marketplace, starting with improvements in the Edison lamp, then the introduction of mercury vapor lamps in the 1930s, followed closely by fluorescent lamps at the 1939 World Fair. Tungsten-halogen lamps were introduced in the 1950s; metal halide and high pressure sodium (HPS) lamps in the 1960s. The introduction of electrodeless lamps in the 1990s is an indication that the industry is dynamic, and the introduction of new light sources is expected to continue at least at the present rate well into the next century. With such a wide selection of light sources on the market, it is likely that several different choices could be made for a given lighting application. While the general characteristics can be provided, a definitive list with absolute values for all types and manufacturers would be too extensive for this chapter. Figure 2-2 provides a comparison of

significant performance characteristics of commonly used lamps. Explanation of the parameters will be provided later in this chapter.

Source Type and Correlated Color Temperature	Lamp Watts	Initial Lumens	Efficacy (LPW)[1]	Lumen Maintenance[2]	Life (Hours)	CRI	Starting and Warmup Time[3] (Minutes)	Dimming Range (Percent Light Output)
Standard incandescent filament, 2700 K	100	1690	17	85	750	100	0	100-0
Tungsten-halogen (linear), 2950 K	300	6000	20	95	2000	100	0	100-0
Tungsten-halogen (reflector), 2850 K	90	1280[5]	14	95	2500	100	0	100-0
Tungsten-halogen (low voltage reflector), 3000 K-3200 K	50	900[5]	18	95	4000	100	0	100-0
Fluorescent T-5 4 ft,[4] 3000 K-4100 K	28	2900[8]	104	95	20,000	85	0	100-1
High output fluorescent T-5 4 ft,[4] 3000 K-4000 K	54	5000[8]	93	95	20,000	85	0	100-1
Fluorescent T-8 4 ft, 3000 K-4100 K	32	2800	88	85	20,000	75	0	100-1
Reduced wattage T-12 4 ft, 3500 K	34	2800	82	85	20,000	73	0	N/A[9]
Slimline reduced wattage 8 ft, 3000 K-5000 K	60	6900	96	80	12,000	85	0	N/A[9]
High output reduced wattage 8 ft, 4100 K	95	8000	84	75	12,000	62	0	100-1
Compact fluorescent (long twin), 3000 K-4100 K	38	3300	87	85	20,000	82	1	100-5
Compact fluorescent (double), 2700 K-4100 K	26	1800	70	85	10,000	82	1	100-5[9]
Mercury vapor, 6800 K	175	7900	45	60	24,000	20	< 10	100-10
Metal halide, low wattage, 3200 K	100	8075	81	85	10,000	70	< 5	100-50[9]
Metal halide, high wattage, 4000 K	400	36,000	90	80	20,000	65	< 10	100-50[9]
HPS, low wattage, 2100 K	70	6300	90	90	24,000	21	< 5	100-50[9]
HPS, high wattage (diffuse), 2100 K	250	26,000	104	90	24,000	21	< 5	100-50[9]

* See manufacturers' catalogs for specific data.
1. Efficacy for lamp is shown. Ballasting is required for all lamps except standard incandescent and tungsten-halogen.
2. Percent of initial lumens for illuminance calculations.
3. Time interval to reach usable light output.
4. Four-pin lamp required.
5. The important performance parameters for reflector lamps are beam angle and maximum center beam intensity.
6. Dimming below the lower value results in significant color shift.
7. Exact lamp length is 1149 mm.
8. Lumen output measured at 35°C (96°F) ambient.
9. Dimming ballasts are currently not available for this lamp.

Figure 2-2 General Characteristics of Commonly Used Light Sources

Figure 2-3 shows shapes of commonly available lamps and Figure 2-4 shows give an explanation of the classification of such shapes. Each lamp shape also includes the corresponding American National Standards Institute (ANSI) designation used by many lamp manufacturers in their catalogs.
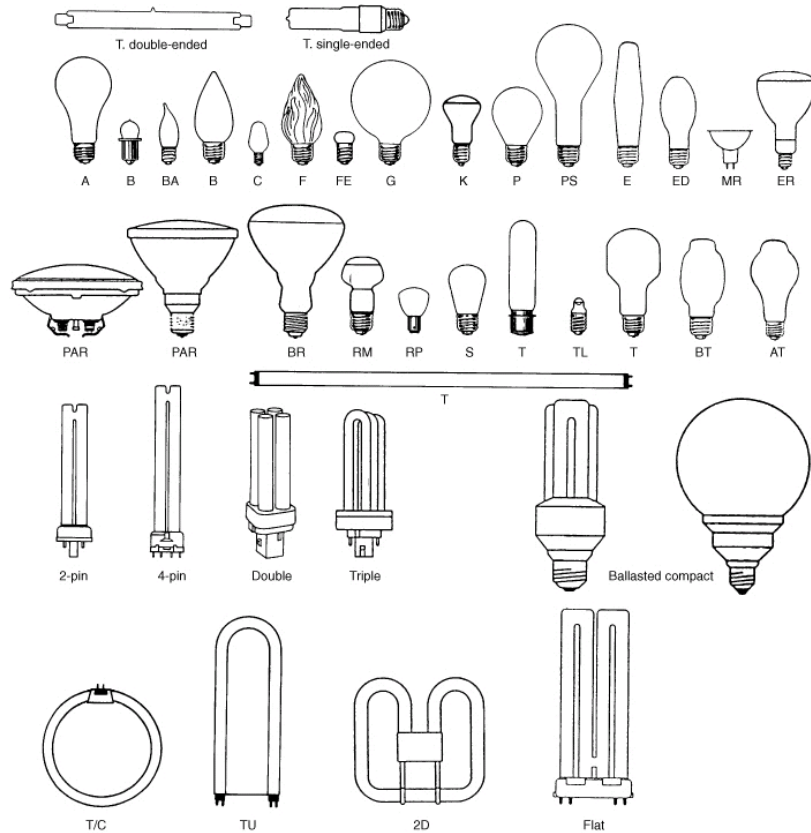
Figure 2-3 Typical bulb shapes (not to scale) and their ANSI designations. Not every ANSI designation, as key-listed here to a descriptive phrase or word, is illustrated.

A–Arbitrary spherical shape tapered to narrow neck
AT–Arbitrary tubular
B–Bulged or bullet shape; blunt tip
BA–Bulged with angular (bent) tip
BD–Bulged with dimple in crown
BR–Bulged reflector
BT–Bulged tubular
C–Conical
CA–Candle shape with bent tip
CC–Two conical shapes blended together (formerly DC)
E–Elliptical
ED–Elliptical with dimple in the crown

ER–Elliptical reflector
F–Flame shape, decorative
FE–Flat elliptical
G–Globe shape
GT–Globe/tubular combination
K–Similar to M but with conical transition
M–Mushroom shape with rounded transitions
MR–Multifaceted reflector
P–Pear shape
PS–Pear shape with straight neck
PAR–Parabolic aluminized reflector
R–Reflector

RB–Bulged reflector (see the more common BR above)
RD–Reflector with dimple in crown
REC–PAR type lamp with rectangular face
RM–Reflector, mushroom shape
RP–Reflector, pear shape
S–Straight-sided shape (compare with CA and BA)
ST–Straight-tipped shape
T–Tubular shape
TL–Tubular shape with lens in crown
T/C–Tubular circular
TU–Tubular U-shape
2D–2-dimensional

Figure 2-4 Bulb Classification

The designation is typically followed by a number, which expresses the diameter of the lamp in multiples of 1/8 inch, so that T-12 refers to a tubular fluorescent lamp with a diameter of 12/8 or 1.5 in. (38 mm), and PAR 30 is a parabolic reflector lamp with a diameter of 30/8 or 3.75 in. (95 mm). Manufacturers use a variety of bases, discussed in the individual lamp sections below. Light sources,

luminaires, controls, and system layout are closely interrelated. A light source that is appropriate for one type of application may be impractical for another.

2.2.   Incandescent filament and tungsten halogen lamps.

The primary consideration of filament lamp design is that it will produce the spectral radiation desired (visible, infrared, ultraviolet) most economically for the application intended. Realization of this objective in an incandescent filament lamp requires the specification of the following: filament material, length, diameter, form, coil spacing, and mandrel size (the mandrel is the form on which the filament is wound); lead-in wires; number of filament supports; filament mounting method; vacuum or filling gas; gas pressure; gas composition; and bulb size, shape, glass composition, and finish. The manufacture of high-quality lamps requires adherence to these specifications and necessitates careful process controls. The construction and principle of operation of incandescent filament and tungsten-halogen lamps are similar; however, the halogen regenerative cycle enables a tungsten-halogen lamp to provide the following benefits compared to a conventional incandescent lamp: longer life, higher color temperature, higher efficacy, and no bulb blackening.

2.2.1.   Incandescent Lamp Construction

2.2.1.1   *Filaments.*

The efficacy of light production depends on the temperature of the filament. The higher the temperature of the filament, the greater the portion of the radiated energy that falls in the visible region. For this reason it is important in the design of a lamp to keep the filament temperature as high as is consistent with satisfactory life. For example, iron is not a good filament material because it melts at a relatively low temperature (1527°C) for efficient light production. Numerous materials have been tested for filament suitability. Desirable properties of filament materials are a high melting point, low vapor pressure, high strength, high ductility, and suitable radiating characteristics and electrical resistance.

2.2.1.2   *Tungsten for Filaments*

Early incandescent lamps used carbon, osmium, and tantalum filaments, but tungsten has many desirable properties for use as an incandescent light source. Its low vapor pressure and high melting point, 3382°C (6120°F), permit high

operating temperatures and consequently high efficacies. Drawn tungsten wire has high strength and ductility, allowing the uniformity necessary for present-day lamps. Alloys of tungsten with other metals such as rhenium are useful in some lamp designs. Thoriated tungsten wire is used in filaments for rough service applications.

2.2.1.3   *Radiating Characteristics of Tungsten*

The ratio of the radiant exitance of a thermal radiator to that of a blackbody radiator is called the emissivity, and thus the emissivity of a blackbody is 1.0 for all wavelengths Tungsten is a selective radiator because its emissivity is a function of the wavelength.
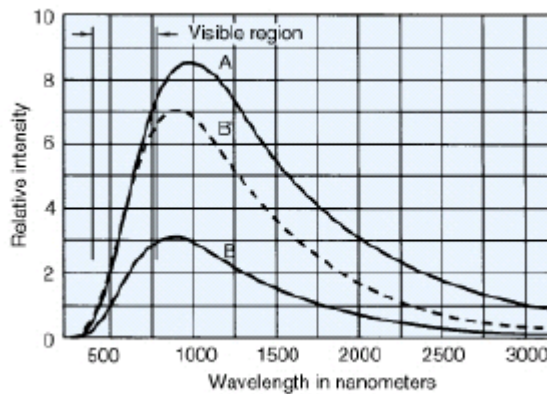
Figure 2-5 Radiating characteristics of tungsten.

Figure 2-5 illustrates the radiation characteristics of tungsten and of a blackbody and shows that for the same amount of visible radiation, tungsten radiates only a percentage of the total radiation from a blackbody at the same temperature. (The intensity of curve B is approximately 76% of curve A.) Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B′: radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.) Only a small percentage of the total radiation from an incandescent source is in the visible region of the spectrum. As the temperature of a tungsten filament is raised, the radiation in the visible region increases, and thus the luminous efficacy increases. The luminous efficacy of an uncoiled tungsten wire at its melting point is approximately 53 lm/W. In order to obtain long life, it is necessary to operate a

filament at a temperature well below the melting point, resulting in a loss in efficacy.

2.2.1.4   *Resistance Characteristics of Tungsten.*

Tungsten has a positive resistance characteristic, so that its resistance at operating temperature is much greater than its cold resistance. In general-service lamps, the hot resistance is 12 to 16 times the cold resistance.

Color Temperature. Often it is important to know the apparent color temperature of an incandescent lamp.
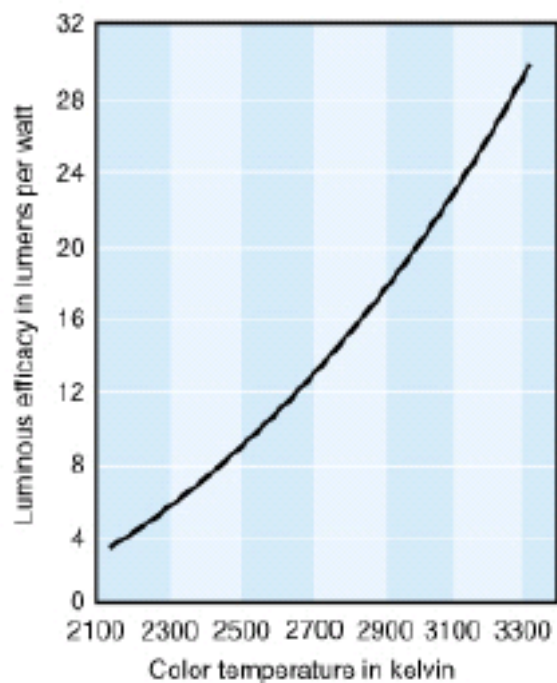
Figure 2-6Variation of color temperature with lamp efficacy.

Figure 2-6 expresses the approximate relationship between color temperature and luminous efficacy for a range of gas-filled lamps. The efficacy value often can be found in the literature, or it can be calculated from published lumen and wattage data. From this value it is possible to approximate the average color temperature of the filament.

2.2.1.5 *Shapes and Size for Bulbs.*

Common bulb shapes are shown in Figure 2-4. Types of Glass for Bulbs. Most bulbs are made of regular lead or soda lime (soft) glass, but some are made of borosilicate heat-resisting (hard) glass. The latter withstand higher temperatures and are used for highly loaded lamps. They usually withstand exposure to moisture or luminaire parts touching the bulb. Three specialized forms of glass are also used as lamp envelopes: fused silica (quartz), high-silica, and aluminosilicate glass. These materials can withstand still higher temperatures.

2.2.1.6 *Bulb Finishes and Colors.*

Inside frosting is applied to many types and sizes of bulbs. It produces moderate diffusion of the light with very little reduction in output. The extremely high filament luminance of clear lamps is reduced, and striations and shadows are mostly eliminated. White lamps having an inside coating of finely powdered white silica provide a better diffusion with little absorption of light. Daylight lamps have bluish glass bulbs that absorb some of the long wavelengths produced by the filament. The transmitted light is of a higher correlated color temperature. This color, achieved at the expense of approximately 35% reduction in light output through absorption, varies between 3500 and 40. General-service incandescent colored lamps are available with inside- and outside-spray-coated, outside-ceramic, transparent-plastic-coated, and natural-colored bulbs. Outside-spray-coated lamps generally are used indoors and not exposed to weather. Their surfaces collect dirt readily and are not easily cleaned. Inside-coated bulbs have smooth outside surfaces that are easily cleaned; thus the pigments are more durable. Ceramic-coated bulbs have the colored pigments fused onto the glass, providing a permanent finish. They are suitable for indoor and outdoor use, as are most transparent-plastic-coated bulbs. The coating permits the filament to be observed directly. Natural-colored bulbs are made of colored glass. Colored reflector lamps use ceramic-coated bulbs, stained bulbs, plastic-coated bulbs, and dichroic interference filters to obtain the desired color characteristics.

2.2.1.7 *Gas Fill.*

Around 1911, attempts were made to reduce the rate of evaporation of the filament by the use of gas-filled bulbs. Nitrogen was first used for this purpose. Although the fill gas reduced bulb-wall blackening, it increased heat loss, leading

to even greater light loss. An incandescent filament operating in an inert gas is surrounded by a thin sheath of heated gas, to which some of the input energy is lost; the proportion lost decreases as the filament diameter is increased. When the filament is coiled in a tight helix, the sheath surrounds the entire coil so that the heat loss is no longer determined by the diameter of the wire but by the diameter of the coil, thus greatly reducing this energy loss. A coiled-coil filament has even less length for a given power rating, thus further reducing the area available for convective cooling. The use of coiled-coil filaments and gas-filled bulbs has yielded major improvement in incandescent lamp efficacies. However, general-service 120-V lamps below 25 W are usually of the vacuum type since gas filling does not improve the luminous efficacy in this wattage range. Inert gases are now preferred because they do not react with the internal parts of the lamp and because they conduct less heat than nitrogen. It was some years after the development of gas-filled lamps before argon became available in sufficient quantity and purity and at reasonable cost. Most lamps are now filled with argon and a small amount of nitrogen; some nitrogen is necessary to suppress arcing between the lead-in wires.

2.2.1.8   *Tungsten-Halogen Lamps.*

The light generation mechanism of tungsten-halogen lamps is the same as that of common incandescent filament lamps, except for the halogen regenerative cycle. Halogen is the name given to a family of electronegative elements, including bromine, chlorine, fluorine, and iodine. Although the tungsten-halogen regenerative cycle has been understood for many years, no practical method of using it was established until the development of small-diameter fused quartz envelopes for filament lamps provided the proper temperature parameters. Iodine was used in the first tungsten-halogen lamp; today, other halogen compounds, predominantly bromine, are used. The regenerative cycle starts with the tungsten filament operating at incandescence, evaporating tungsten off the filament. Normally the tungsten particles would collect on the bulb wall, resulting in bulb blackening, common with incandescent lamps and most evident near the end of their life. However, in halogen lamps the temperature of the bulb is high enough so that the tungsten combines with the halogen. The correlated minimum temperature of the bulb must be approximately 260°C (500°F). The resulting tungsten-halogen compound is also gaseous and continues to circulate inside the lamp until it comes in contact with the incandescent filament. Here, the heat is

sufficient to break down the compound into tungsten, which is redeposited on the filament, and halogen, which is freed to continue its role in the regenerative cycle. However, since the tungsten does not necessarily redeposit exactly where it came from, the tungsten-halogen lamp still has a finite life. Dimmed tungsten-halogen lamps should periodically be run at full power, inducing the tungsten-halogen cycle to clean the tungsten off the bulb wall, and thereby maintaining lamp efficacy over time.

2.2.2. Performance Parameters

2.2.2.1 *Energy Characteristics*

The manner in which the energy input to a lamp is dissipated can be seen in Figure 2-7 below for typical general-service lamps.

Watts	Radiated in visible spectrum (percent of input wattage)	Total filament radiation beyond bulb (percent of input wattage)	Gas loss (percent of input wattage)	Base and bulb loss (percent of input wattage)	End loss (loss by conduction at filament ends in percent of input wattage)	Filament heat current (J)	Heating time to 90 percent lumens (s)	Cooling time to 10 percent lumens (s)
6*	6	93.0	—	5.5	1.5	0.25	0.04	0.01
0*	7.1	93.5	—	5.0	1.5	0.62	0.06	0.02
5*	8.7	94.0	—	4.5	1.5	2.8	0.10	0.03
40†	7.4	71.3	20.0	7.1	1.6	2.5	0.07	0.03
60‡	7.5	80.8	13.5	4.5	1.2	5.5	0.10	0.04
100‡	10.0	82.0	11.5	5.2	1.3	14.1	0.13	0.06
200†	10.2	77.4	13.7	7.2	1.7	39.5	0.22	0.09
300†	11.1	79.8	11.6	6.8	1.8	80.0	0.27	0.13
500†	12.0	82.3	8.8	7.1	1.8	182.0	0.38	0.19
1000†	12.1	87.4	6.0	4.7	1.9	566.0	0.67	0.30

Figure 2-7 Luminous and Thermal Charateristics of Typical Incandescent Filament

The radiation in the visible spectrum (column 2) is the percentage of the input power actually converted to visible radiation. The gas loss (column 4) indicates the amount of heat lost by the filament due to the conduction through and convection by the surrounding gas in gas-filled lamps. The end loss (column 6) is the heat lost from the filament by the lead-in wires and support hooks which conduct heat from the filament. Column 3 shows the total radiation beyond the bulb, which is less than the actual filament radiation due to absorption by the glass bulb and the lamp base. Incandescent lamps operated below 25 Hz will produce perceptible flicker and can create a stroboscopic effect. Flicker will be less from an incandescent source if it has a larger filament and is operated at a higher wattage and at a higher supply frequency. Modern incandescent light

sources operated at 60 Hz do not produce noticeable flicker, nor a stroboscopic effect, to the human eye.

2.2.2.2   *Bulb and Socket Temperatures.*

Incandescent filament lamp operating temperatures are important for several reasons. Excessive lamp temperature can affect lamp life, luminaire life, and the life of the electrical supply circuit. High temperatures can ignite combustible materials that form a part of the luminaire or those adjacent to the luminaire. Under certain atmosphere or dust conditions, high bulb temperatures (above 160°C [320°F]) can induce explosion or fire.

2.2.2.3   *Lamp Characteristics*

Life, Efficacy, Color Temperature, and Voltage Relationships. If the voltage applied to an incandescent filament lamp is varied, there is a resulting change in the filament resistance and temperature, current, power, light output, efficacy, and life. These characteristics are interrelated, and not one of them can be changed without affecting the others. The following equations can be used to calculate the effect of a change from the design conditions on lamp performance (capital letters represent normal rated values; lowercase letters represent changed values):

$$\frac{life}{LIFE} = \left(\frac{VOLTS}{volts} \right)^{d}$$

2-1

$$\frac{lumens}{LUMENS} = \left(\frac{VOLTS}{volts} \right)^{g}$$

2-2

$$\frac{lpw}{LPW} = \left(\frac{VOLTS}{volts} \right)^{n}$$

2-3

$$\frac{watts}{WATTS} = \left(\frac{VOLTS}{volts} \right)^{n}$$

2-4

$$\frac{color \quad temperature}{COLOR \quad TEMPERATURE} = \left(\frac{VOLTS}{volts} \right)^{m}$$

2-5

For approximations, the following exponents may be used in the above equations: d = 13, g = 1.9, k = 3.4, n = 1.6, and m = 0.42. For more accuracy, the exponents must be determined by each lamp manufacturer from a comparison of normal-voltage and over- or undervoltage tests of many lamp groups. Exponents vary for different lamp types, lamp wattages, and ranges of percentage voltage variation. The values given above are roughly applicable to vacuum lamps of approximately 10 lm/W and gas-filled lamps of approximately 16 lm/W in a voltage range of 90 to 110% of rated voltage.

a)

b)
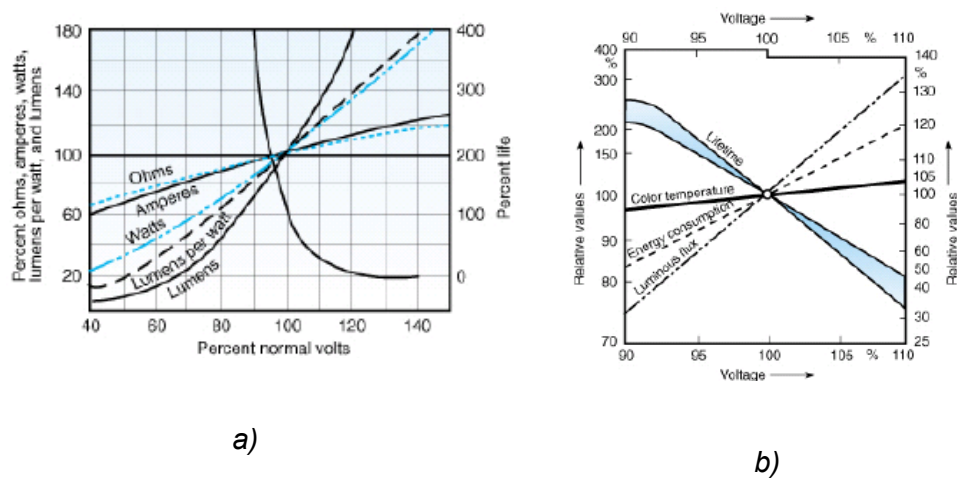
Figure 2-8 Effect of voltage and current variation on the operating characteristics of: (a) incandescent filament lamps in general lighting (multiple) circuits and (b) tungsten-halogen lamps in series street lighting circuits.

The curves of Figure 2-8 show the effect of voltage variations on lamps in general lighting (multiple) circuits. The effect of voltage variation on the characteristics of tungsten-halogen lamps cannot be accurately predicted outside of the voltage range of 90 to 110% of the rated voltage.

2.2.2.4 *Depreciation During Life.*

Over a period of time, incandescent filaments evaporate and become smaller, which increases their resistance. In multiple circuits, the increase in filament resistance reduces current, power, and light. A further reduction in light output is caused by the absorption of light by the deposit of the evaporated tungsten particles on the bulb.

2.2.2.5   *Lamp Mortality.*

 Many factors inherent in the manufacturing process make it impossible for every lamp to achieve the rated life for which it was designed. For this reason, lamp life is rated as the average of a large group.

2.2.2.6   *Dimming of Incandescent and Tungsten-Halogen Lamps.*

Dimmers today have a dual purpose: energy conservation and aesthetic lighting effects. Incandescent lamps can be dimmed simply by lowering the voltage across the lamp filament. When the voltage is lowered, less power is dissipated and less light is produced with a lower color temperature. An added benefit is an increase in the life of an incandescent lamp. For example, when an incandescent lamp is operated at 80% rated voltage using a dimmer, its life is increased by a factor of nearly 20. In a tungsten-halogen lamp, the life of the filament depends on voltage just as with standard incandescent filament lamps. However, because the regenerative halogen cycle stops when bulb wall temperature falls below 260°C (500°F), the tungsten halogen lamp blackens and its useful life is not extended by nearly the same factor as that of standard lamps. This can be partially compensated for by periodically operating the lamp near or at full light output, which helps clean the lamp of tungsten deposits.

In the 1950s, rheostats were used for dimming by regulating the lamp current in an incandescent lamp. They were large and inefficient. Today, most dimmers are electronic, using thyristor and transistor circuits that have low power dissipation. Modern dimmers are efficient and reduce power as the source is dimmed. Thyristors operate as high-speed switches that rapidly turn the voltage to the lamp on and off. This switching can cause electromagnetic interference with other electrical equipment as well as audible buzzing in the lamp filament. Magnetic coils known as chokes are usually used as filters to reduce these effects. With many wall-box dimmers, however, lamp buzzing cannot be completely eliminated because a larger choke is needed than space allows. For these cases, remotely mounted, properly sized lamp debuzzing coils or additional chokes are recommended.

2.2.2.7   *Classification of Incandescent and Tungsten-Halogen Lamps*

Incandescent filament lamps were historically divided into three major groups: large lamps, miniature lamps, and specialty lamps. They also were cataloged

separately by lamp manufacturers. There is no sharp dividing line among the groups, and they are usually included in the same catalog by the manufacturer. The list below classifies lamps into four categories for the purposes of illustrating their applications:

- general lamps,

- dedicated application lamps

- low-voltage miniature

- sealed beam lamps, and photographic and photo-optical lamps

2.3.   Fluorescent Lamps

The fluorescent lamp is a low-pressure gas discharge source, in which light is produced predominantly by fluorescent powders activated by UV energy generated by a mercury arc. The lamp, usually in the form of a long tubular bulb with an electrode sealed into each end, contains mercury vapor at low pressure with a small amount of inert gas for starting. The inner walls of the bulb are coated with fluorescent powders commonly called phosphors. When the proper voltage is applied, an arc is produced by current flowing between the electrodes through the mercury vapor. This discharge generates some visible radiation, but mostly invisible UV radiation, the principal lines being approximately 254, 313, 365, 405, 436, 546, and 578 nm. The UV in turn excites the phosphors to emit light. The phosphors are generally selected and blended to respond most efficiently to 254 nm, the primary wavelength generated in a mercury low-pressure discharge. Like most gas discharge lamps, fluorescent lamps must be operated in series with a current-limiting device. This auxiliary, commonly called ballast, limits the current to the value for which each lamp is designed. It also provides the required starting and operating lamp voltages and may provide dimming control.

2.3.1.   Lamp Construction

Bulbs. Linear fluorescent lamps are commonly made with straight, tubular bulbs varying in diameter from approximately 6 mm (0.25 in. T-2) to 54 mm. (2.125 in. T-17) and in overall length from a nominal 100 to 2440 mm (4 to 96 in.). The bulb is historically designated by a letter indicating the shape, followed by a number indicating the maximum diameter in eighths of an inch. Hence T-8 indicates a

tubular bulb 8/8 in., or 1 in. (26 mm), in diameter. The nominal length of the lamp includes the thickness of the standard lampholders and is the back-to-back dimension of the lampholders with a seated lamp. Fluorescent lamps also come in shapes other than straight tubes. U-shaped tubes are formed by bending tubes in half. They are commonly used in 0.61 m (2 ft) square luminaires. Circular (circline) lamps are tubes bent in a circle with the two ends adjacent to each other. In increasing use are smaller diameter, single-ended, compact fluorescent lamps consisting of multiple shaped tubes joined together to form a continuous arc path. They are designed to approach the size of the incandescent lamp.
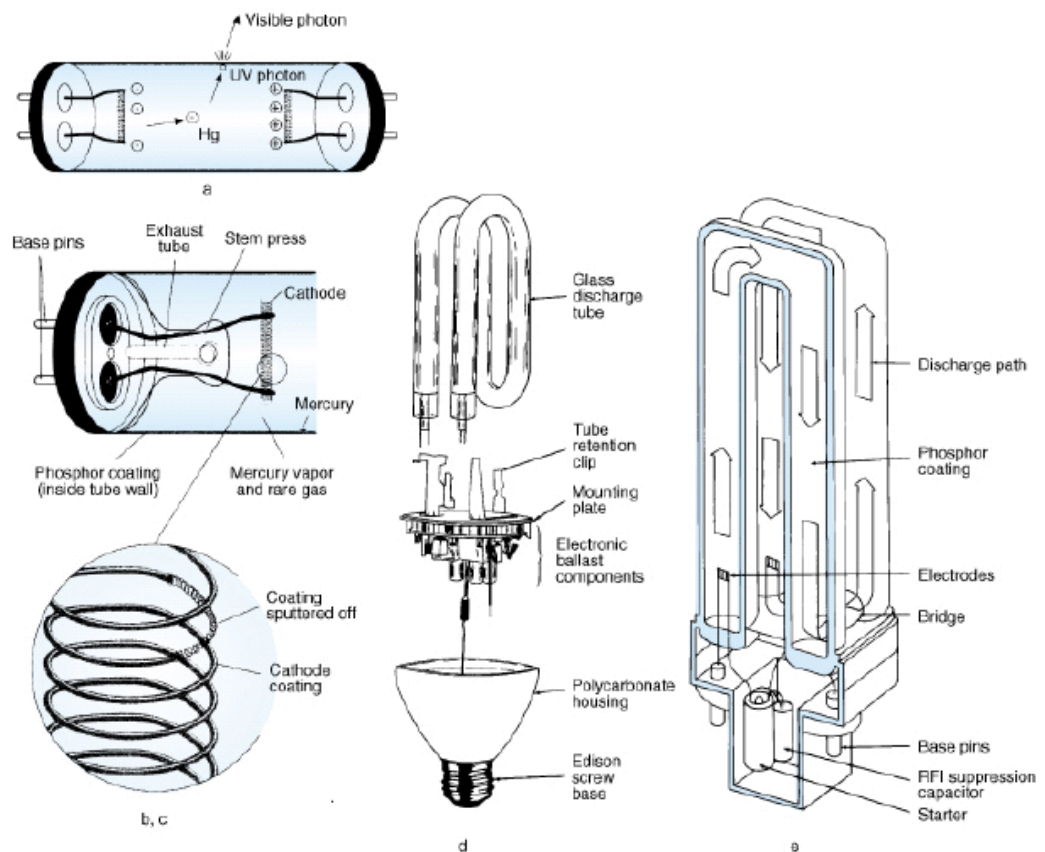
Figure 2-9 Cutaway view of some common fluorescent lamps: (a) A typical rapid-start fluorescent lamp and the production of light; (b) lamp electrode construction; (c) detail of the electrode; (d) a screw-in compact fluorescent lamp with built-in ballast; (e) a 2-pin plug-in compact fluorescent lamp with built-in starter.

Commonly used lamp designations are shown in Figure 2-9. The 32 W T-8 lamp is used as an example, but the designations for most fluorescent lamps follow the same principles.

2.3.1.1   *Nomenclature for Fluorescent Lamps.*

 Fluorescent lamps can be designated as illustrated in Figure 2-10. This is only one example; often manufacturers will adopt variations.

F	32	T8	RE735	/ES/HO
(a)	(b)	(c)	(d)	(e)

(a) Lamp type. "F" is used for fluorescent lamps. "FB" or "FU" is used for U-bent lamps, while "FT" is used for twin-tube lamps.

(b) Wattage for preheat and rapid start lamps; or lamp length (in.) for slimline and HO lamps.

(c) Diameter of tube (in eighths of an inch). "T8" is a 1-in. diameter tube, and "T12" is a 1.5-in. diameter tube.

(d) Lamp color (sometimes omitted). "RE" indicates a rare earth phosphor; "7" represents the first digit of the CRI (between 70 and 79); "35" represents the first two digits of the CCT (between 3500 and 3599). For halophosphate lamps, the color might be represented as in these examples: "CW" for cool white or "WW" for warm white.

(e) Optional modifiers. "ES" represents an energy saving lamp; "HO" is high output; "VHO" is very high output. These are often preceded with a slash ("/").

Figure 2-10 Nomenclature of Fluorescent Lamps

2.3.1.2   *Electrodes.*

Two electrodes are hermetically sealed into the bulb, one at each end. These electrodes are designed for operation as either cold or hot cathodes, more correctly called glow or arc modes of discharge operation. Electrodes for glow (cold cathode) operation can consist of closed-end metal cylinders, generally coated on the inside with an emissive material. Cold cathode lamps operate at a few hundred milliamperes, with a high value of the cathode fall (the voltage required to create ion and electron current flow) in excess of 50 V. The arc mode (hot cathode) electrode generally is constructed from a single tungsten wire, or a tungsten wire around which another very fine tungsten wire has been uniformly wound. The larger tungsten wire is coiled, producing a triple-coil electrode. When the fine wire is absent, the electrode is referred to as a coiled-coil electrode. The coiled-coil or triple-coil tungsten wire is coated with a mixture of alkaline earth oxides to enhance electron emission. During lamp operation, the coil and coating reach temperatures of approximately 1100°C (2012°F), at which point the coil-and-coating combination thermally emits large quantities of electrons at a low cathode fall, in the range of 10 to 12 V. The normal operating current of arc mode

lamps is approximately 1.5 A or less. As a consequence of the lower cathode fall associated with the hot cathode, more efficient lamp operation is obtained, and therefore most fluorescent lamps are designed for such operation.
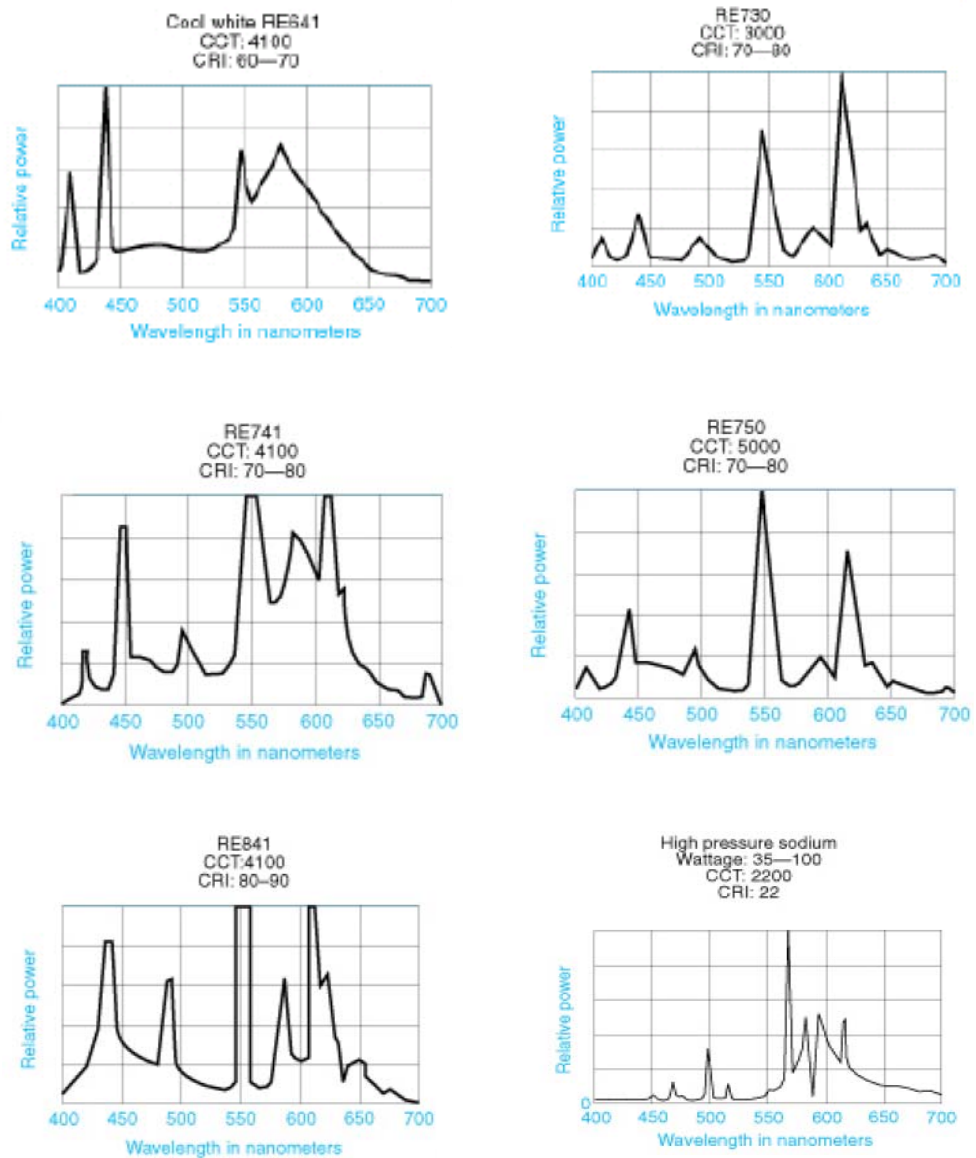
Figure 2-11Spectral power distribution charts for various types of fluorescent lamps and HID lamps.

2.3.1.3   *Gas Fill.*

The operation of the fluorescent lamp depends on the development of a discharge between the two electrodes sealed at the extremities of the lamp bulb. This discharge is developed by ionization of mercury gas contained in the bulb. The mercury gas is typically maintained at a pressure of approximately 1.07 Pa (0.00016 lb/in.2), which is the vapor pressure of liquid mercury at 40°C (104°F), the optimum bulb wall temperature of operation for which most lamps are designed (see the section "Temperature Effect on Operation" below). In addition to the mercury, a rare gas or a combination of gases at low pressure, from 100 to 400 Pascals (0.015 to 0.058 lb/in.2), is added to the lamp to facilitate ignition of the discharge. Standard lamps employ argon gas; energy-saving types, a mixture of krypton and argon; others, a combination of neon and argon or of neon, xenon, and argon.

2.3.1.4   *Phosphors*

The color of the light produced by a fluorescent lamp depends on the blend of phosphors used to coat the wall of the tube. Many different white and colored fluorescent lamps are available, each having its own characteristic spectral power distribution. These types have a combination of continuous and line spectra. Popular fluorescent lamps use three highly efficient narrow-band, rare-earth activated phosphors with emission peaks in the short-, middle-, and long-wavelength regions of the visible spectrum. These triphosphor lamps can be obtained with high color rendering, improved lumen maintenance, and good efficacy with correlated color temperatures between 2500 and 6000 K relative to halophosphate lamps. Since the rare-earth phosphors are expensive, the longer T-5, T-8, T-10, and T-12 triphosphor lamps typically employ a two-coat system consisting of a less expensive halophosphate phosphor applied with the rare-earth type. The rare-earth activated phosphor is closest to the mercury discharge and, as a result, the spectral power distribution of the lamp is more influenced by these phosphors. Common commercial types have correlated color temperatures of 3000, 3500, and 4100 K. A variety of lamp types is available that radiate in particular wavelength regions for specific purposes, such as plant growth, merchandise enhancement, and medical therapy. Various colored lamps, such as blue, green, and gold, are obtained by phosphor selection and filtration through pigments.

2.3.1.5   *Bases.*

For satisfactory performance, a fluorescent lamp must be connected to a ballasted electrical circuit with proper voltage and current characteristics for its type. Several fluorescent lamp base designs are used. The bases physically support the lamp in most cases and provide a means of electrical connection. Straight tube lamps designed for instant-start operation (see the section "Instant-Start Lamp and Ballast Operation" below) generally have a single connection at each end. As a consequence, a single-pin base is satisfactory. Preheat and rapid-start lamps (see the section "Lamp Starting" below) have four electrical connections, two at each end of the tube, and therefore require dual-contact bases. In the case of the circline lamp, a single four-pin connector is required. Many compact fluorescent lamp bases have unique designs to help ensure their use with the correct ballast. Single-ended compact fluorescent lamps with integral starters have plastic bases containing a glow switch and a noise reduction filter capacitor. These bases have two connection pins. Some lamp wattages are available without the starting components mounted within the bases and have four connection pins.(Figure 2-12). Only four-pin lamps are dimmable. For incandescent lamp retrofit applications, self-ballasted compact fluorescent lamps have medium screw bases.
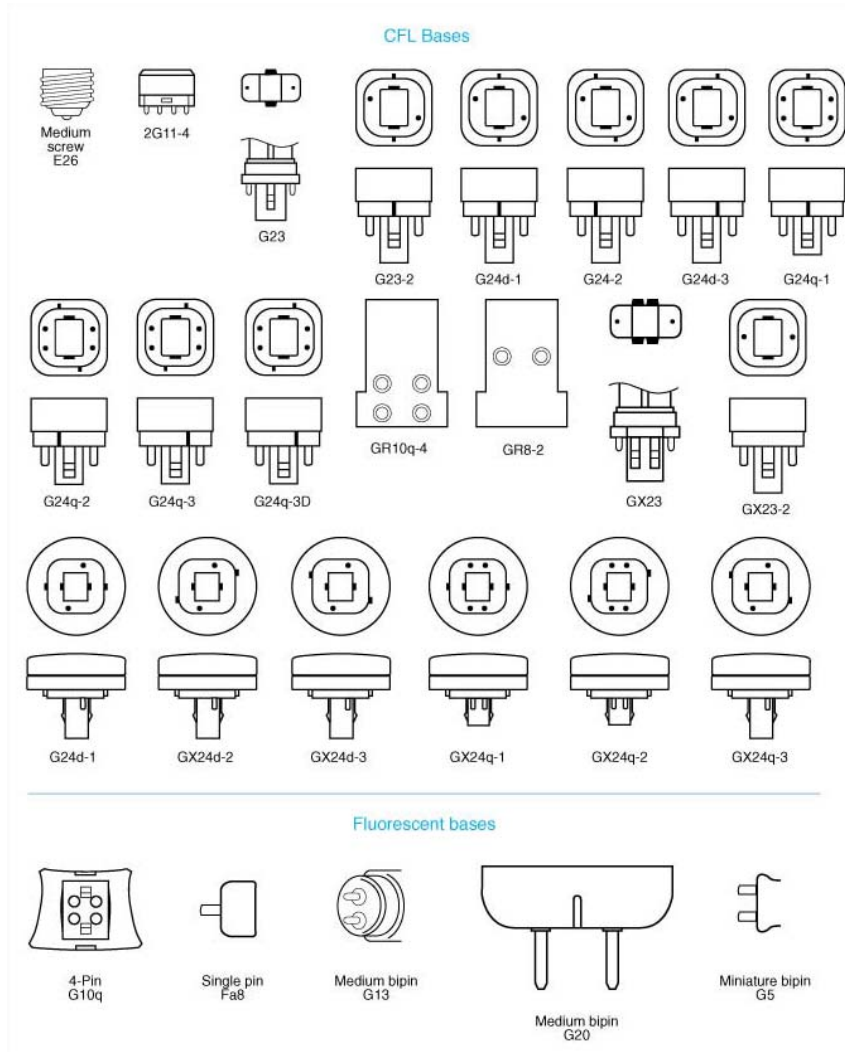
Figure 2-12. Typical bases for linear and compact fluorescent lamps (not to scale). ANSI designations are shown.

2.3.2. Common Fluorescent Lamp Families

2.3.2.1 *T-12 Fluorescent Lamps.*

Until the National Energy Policy Act of 1992 (EPACT), the most commonly applied fluorescent lamp in the United States and Canada was the T-12, 40-W, 4-ft (1.22-m), rapid-start lamp with a cool white or warm white phosphor. EPACT banned the production of these type lamps after 1995. EPACT also impacted the T-12, 8-ft (2.44 m) lamps. As with 4-ft lamps, only reduced wattage or improved color rendition lamps are currently produced for U.S. consumption. For many new installations, the more efficient T-8 lamps are often specified. Legislation similar to EPACT exists in Canada, where energy efficiency standards for fluorescent

lamp ballasts, fluorescent lamps, and incandescent reflector lamps have been established under the Energy Efficiency Act. Regulated products cannot be imported into Canada or traded between its provinces unless they meet the regulatory requirements.

2.3.2.2   *Energy-Saving Fluorescent Lamps.*

In response to the energy crisis of the 1970s, lamp companies introduced halophosphate T-12 lamps filled with an argon-krypton gas mixture, rather than argon only. The 4-ft (1.22 m) lamps can be operated suitably on a ballast designed for 4-ft (1.22 m) 40-W lamps, but because of the different gas mixture they dissipate approximately 34 W per lamp. Any of the energy-saving ballasts that operate standard lamps at full light output can be used, provided the ballast is listed for use with the lamps; this information is stated on the ballast label. These lamps may not be used with any ballast that provides reduced wattage and thus reduced light output in a standard lamp, nor with any ballast that does not list the lamp on its label. A transparent conductive coating is applied to these energy-saving lamps, resulting in a lower required starting voltage and less lumen output. By using these lamps as a retrofit in over illuminated spaces, a saving of 5 to 6 W per lamp can be achieved. Whether operated on standard or energy-efficient magnetic ballasts, energy-saving fluorescent lamps generate approximately 87% of the light generated by a standard (40-W T-12) lamp at 25°C (77°F). This lamp-ballast system is less efficient than the standard argon gas lamp-ballast system, since it generates fewer lumens per watt. This is due to increased ballast losses. In addition, these lamps cannot be dimmed as easily as standard T-12 lamps, and they are more sensitive to temperature, especially in regard to starting, and should not be started or operated at low temperatures.

2.3.2.3   *T-8 Fluorescent Lamps.*

T-8 fluorescent lamps are a family of 1-in.-diameter (25.4 mm) straight tube lamps manufactured in some of the same lengths as T-12 lamps. The 4-ft version of the lamp is designed to consume approximately 32 W. It is also available in 2-, 3-, 5- and 8-ft. (0.16-, 0.91-, 1.52-, and 2.44-m) lengths. The smaller diameter makes it economical to use the more efficient and more expensive rare-earth phosphors. Although the T-8 ad T-12 lamps are physically interchangeable, they cannot operate on the same ballast. T-8 lamps are designed to operate on line-

frequency rapid-start ballasting systems at approximately 265 mA, or on high-frequency electronic ballasts at slightly less current. Due to the higher efficacies that can be reached with T-8 systems, they have replaced the conventional T-12 lamps in many applications.

2.3.2.4   *T-5 Fluorescent Lamps.*

T-5 fluorescent lamps are a family of smaller diameter straight tube lamps employing triphosphor technology. Available only in metric lengths and mini bipin bases, the T-5 lamps provide a higher source brightness than T-8 lamps and better optical control. The lamps provide optimum light output at an ambient temperature of 35°C (95°F) rather than the more typical 25°C (77°F), allowing for the design of more compact luminaires. Also available are high-output versions providing approximately twice the lumens at the same length as the standard versions. T-5 lamps are designed to operate solely on electronic ballasts. Their unique lengths, special lampholder, and ballast requirements make them unsuitable for most retrofit applications. These lamps are used in shallower luminaires than the T-8 lamps, which are more efficient over all than luminaires for T-8 lamps.

2.3.2.5   *Compact Fluorescent Lamps*

The rare-earth activated phosphor has led to the development of a growing variety of multitube or multibend single-ended lamps known as compact fluorescent lamps (CFLs). The lamps originally were designed to be interchangeable with conventional 25- to 100-W incandescent lamps, but now this lamp type includes sizes that replace conventional fluorescent lamps in smaller luminaires. T-4 and T-5 tubes typically are used in compact fluorescent lamps. There are many techniques of adding, bending, and connecting the tubes to obtain the physical size and lumen output desired. The tube portion of the lamp is sometimes enclosed in a cylindrical or spherical outer translucent jacket made of glass or plastic. Some lamps contain the lamp starter, while others contain both the starter and the ballast, which can take the form of a simple magnetic choke or an electronic ballast. Present compact lamp wattages vary from 5 to 55 W, and rated lumen output ranges from 250 to 4800 lm. Overall lamp length varies from 100 to 570 mm (3.93 to 22.4 in.), depending on lamp wattage and construction. Some designs with self-contained ballasts are equipped with

Edison-type screw-in bases for use in incandescent sockets (Figure 2-9d), while other designs use special pin-type bases for dedicated use with mating sockets designed for lamps of a particular wattage (Figure 2-9e). Because of the high power density in these lamps, high-performance phosphors are used extensively in order to enhance brightness, lumen maintenance, and color rendering ability. Amalgams can be added to some versions to enhance performance under a range of operating temperatures.

2.3.3.   Performance Parameters

Figure 2-2 lists several performance parameters for many common fluorescent lamps. These parameters are discussed in more detail below.

2.3.3.1   Luminous Efficacy:Light Output.

Three main energy conversions occur in a fluorescent lamp. Initially, electrical energy is converted into kinetic energy by accelerating charged particles. These in turn yield their energy during particle collision to electromagnetic radiation, particularly UV. This UV energy in turn is converted to visible energy by the lamp phosphor. During each conversion some energy is lost, so that only a small percentage of the input is converted into visible radiation. Figure 2-13 shows the approximate energy distribution in a typical cool white fluorescent lamp.
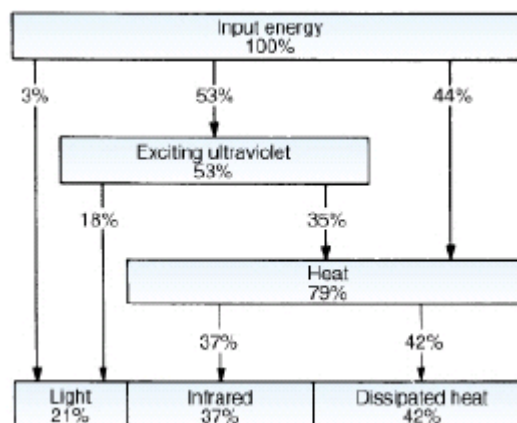
Figure 2-13 Energy distribution in a typical cool white fluorescent lamp.

2.3.3.2 *Lamp Life.*

The lamp life of hot cathode lamps is determined by the rate of loss of the emissive coating on the electrodes (Figure 2-9 b and c). Some of the coating is eroded from the filaments each time the lamp is started. Emissive coating also is lost by evaporation during normal lamp operation. Electrodes are designed to minimize both of these effects. The end of lamp life is reached when either the coating is completely removed from one or both electrodes, or the remaining coating becomes nonemissive. Because some of the emissive coating is lost from the electrodes during each start, the frequency of starting hot cathode lamps influences lamp life. The rated average life of fluorescent lamps usually is based on three hours of operation per start (3 h/start). Some electronic ballasts have been designed to instant start rapid-start T-8 and T-12 lamps. Typically there is a 25% reduction in lamp life based upon 3 h/start. Many other conditions affect lamp life. Ballast characteristics and starter design are key factors for preheat circuits. Ballasts that neither provide specified starting requirements nor operate lamps at proper voltage levels can greatly affect lamp life.

2.3.3.3 *Lumen Depreciation.*

The light output of fluorescent lamps decreases with accumulated operating time because of photochemical degradation of the phosphor coating and glass tube and the accumulation of light-absorbing deposits within the lamp. The rate of phosphor degradation increases with arc power and decreases with increased coating density. Lamp lumen depreciation (LLD) curves for different fluorescent lamps are shown in Figure 2-15. Protective coatings are sometimes used to reduce the phosphor degradation. Triphosphors are more stable and allow higher loading levels, as for example in T-5, T-8, compact, and subminiature lamps. The deposit of electrode coating material evaporated during lamp operation causes end darkening. This reduces UV radiation into the phosphors, thereby reducing light output near the ends.
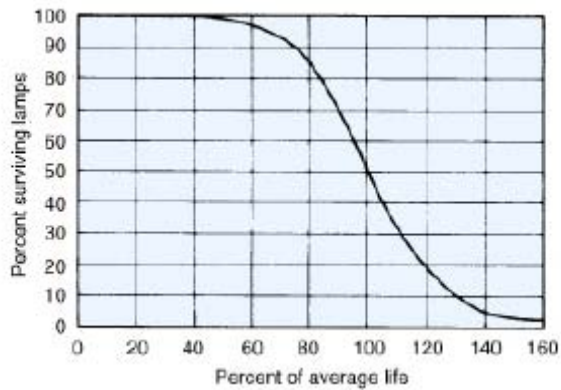
Figure 2-14. Typical mortality curve for a statistically large group of fluorescent lamps (at 3 operating hours per start).
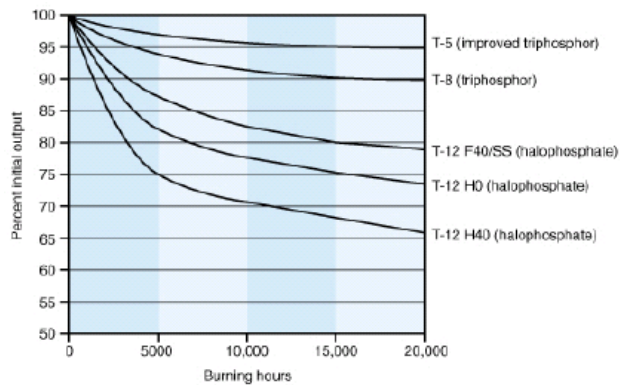
Figure 2-15 Fluorescent lamp lumen depreciation (based on operating on suitable ballast at 3 hr per start).

2.3.3.4   Spectral Power Distribution and Chromaticity.

Spectral power distribution data for several fluorescent lamps are shown in Figure 2-11.

2.3.3.5   Temperature Effect on Operation.

The luminous performance, light output, and color of a fluorescent lamp are dependent on the mercury vapor pressure within the lamp, which depends on temperature.

2.3.3.6   Effects of Temperature on Color.

The color of light from a fluorescent lamp depends on the phosphor coating and also the mercury arc discharge. Each of these components reacts differently to temperature changes. Figure 2-16 shows a typical color shift characteristic of a halophosphate fluorescent lamp.
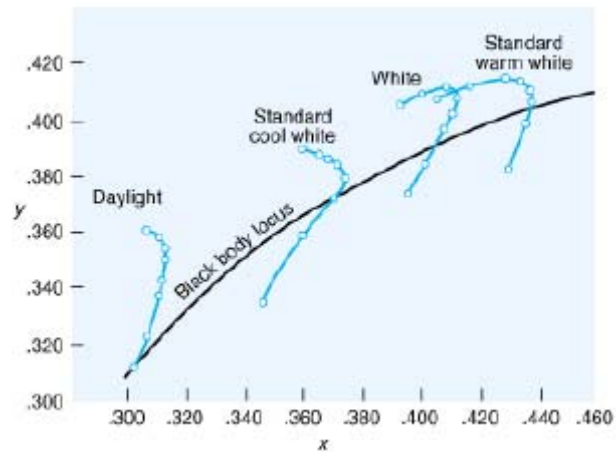
Figure 2-16. This CIE chromaticity diagram contains data for four different halophosphate fluorescent lamps. It shows that the color each lamp produces shifts toward the blue/green with increasing temperature. The lowest point on each curve is at −20°C (−4°F). Following each curve up and to the left as it bends over, the furthest point is at 120°C (248°F). Intermediate points are 20°C (36°F) apart. The chromaticity coordinates of any point are obtained from the x and y axis.

2.3.3.7   High-Frequency Operation of Fluorescent Lamps.

High-frequency electronic ballasts generally provide power to the fluorescent lamp in the range of 10 to 50 kHz from a 50- to 60-Hz power supply. The primary advantage of high-frequency electronic ballasts for fluorescent lighting systems is higher efficacy relative to the 60-Hz magnetic ballast systems. As shown in Figure 2-17, efficacy increases rapidly with high-frequency operation until 20 kHz; in the range from 20 to 100 kHz, efficacy is constant. The improved performance of the fluorescent lamp at high frequencies has been attributed to two factors. First, a reduction in end losses is achieved by elimination of the oscillation on the anode half of the operating cycle. Second, an increase in efficiency of the lamp's positive column (major portion of the arc stream) is achieved by operating at lower wattage. In order to save energy, fluorescent lamps normally are operated at lower than rated wattage with high-frequency electronic ballasts while

maintaining the lamp's rated lumen output. In order to avoid audible noise, most electronic ballasts operate the lamp above 20 to 30 kHz. Another consideration in high-frequency operation of fluorescent lamps is radiated and conducted radio-frequency (RF) noise.
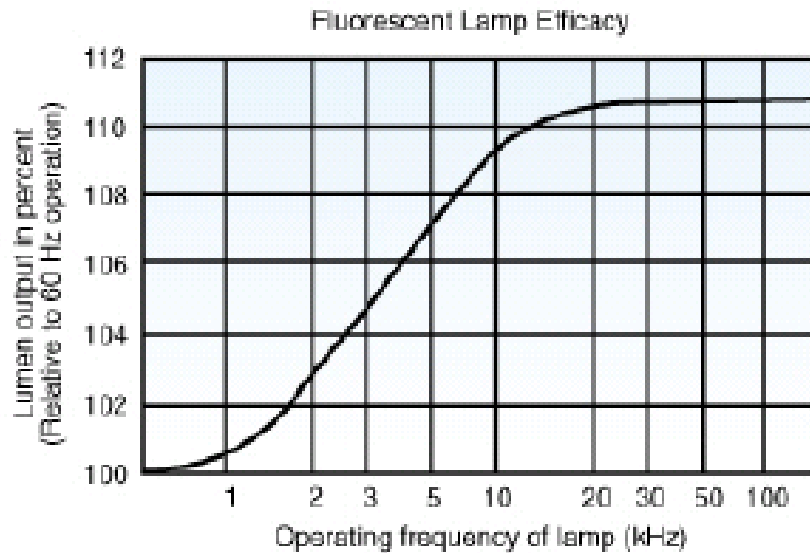
Figure 2-17 Lamp efficacy gain at constant lumen output vs. operating frequency for a 40-watt, T-12 rapid-start lamp.

2.3.3.8   Flicker and Stroboscopic Effect.

The light output of a fluorescent lamp varies with instantaneous power input. Operating on a magnetic ballast with a 60-Hz power input frequency, the resulting 120-Hz variation coupled with phosphor persistence makes the fluctuating light output too rapid for most people to perceive. This assumes, however, that the power input is free of electrical noise. The presence of electrical noise from other equipment can result in frequencies that manifest themselves as visible flicker. Under noise-free operating conditions, the flicker index for typical fluorescent lamps operated with electromagnetic ballasts ranges from 0.01 to approximately 0.1, and is much lower when operated with high frequency electronic ballasts.

2.3.4.   Lamp Operation and Auxiliary Equipment

Fluorescent lamps have a negative volt-ampere characteristic and therefore require an auxiliary device to limit current flow. This device, called a ballast, might also provide a voltage sufficient to start the arc discharge. This voltage can vary

between 1.5 to 4 times the normal lamp operating voltage. The life and light output ratings of fluorescent lamps are based on their use with ballasts providing proper operating characteristics, which have been established in the ANSI standards for dimensional and electrical characteristics of fluorescent lamps (C78 Series). Ballasts that do not provide proper electrical values might reduce either lamp life or light output or both. This auxiliary equipment requires electrical power and therefore reduces the system efficacy below that based on the power requirements of the lamp.

2.3.4.1 *Lamp Starting.*

The starting of a fluorescent lamp occurs in two stages. First, the electrodes must be heated to their emission temperatures. Second, a sufficient voltage must exist across the lamp to ionize the gas in the lamp and develop the arc. In some starting systems, a voltage is applied between one of the electrodes and ground to help ionization.

2.3.4.2 *Ballasts*

2.3.4.2.1 *Magnetic Ballasts.*

The construction of a typical thermally protected rapid-start magnetic ballast is shown in Figure 2-19.
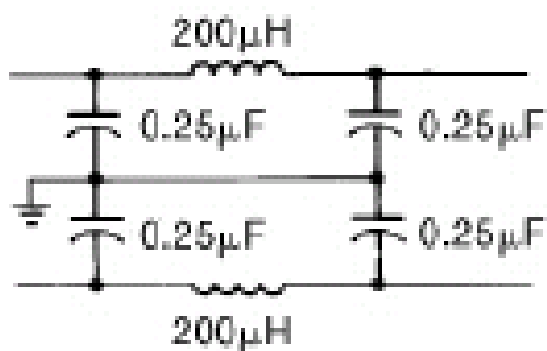
Figure 2-18 Typical radio interference filter.
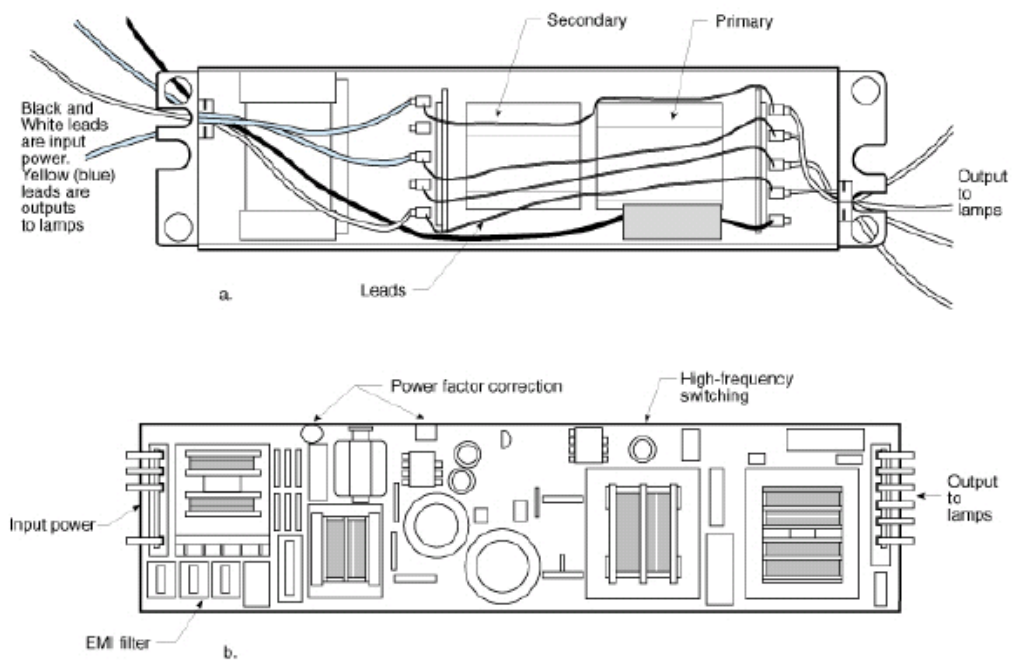
Figure 2-19 Components of a magnetic ballast (a) and high-frequency electronic ballast (b) for a linear fluorescent lamp.

The components include a transformer-type core and coil. A capacitor might be included. These components are the heart of the ballast, providing sufficient voltage for lamp ignition and lamp current regulation through their reactance. The core-and-coil assembly is made of laminated transformer steel wound with copper or aluminum magnet wire. The assembly is impregnated with a nonelectrical insulation to aid in heat dissipation and, with leads attached, is placed in a case. The case is filled with a potting material (e.g., hot asphalt) containing a filler such as silica. This compound completely fills the case, encapsulating the core and coil and the capacitor. The base is then attached. The average ballast life at a 50% duty cycle and a proper ballast operating temperature is normally estimated at twelve years.

2.3.4.2.2   Electronic Ballasts.

The operating frequency of electronic ballasts is chosen to be high enough to increase the lamp efficacy and to make ballast noise inaudible, but not so high as to cause electromagnetic interference (EMI). Electronic ballasts also provide a level of light output regulation that is unavailable in totally passive, magnetic ballasts. Designs are available for the rapid- and instant-start of lamps. Some electronic ballasts are designed to operate up to four lamps each. Many are

made in the same size and shape as magnetic units in order to ease direct replacement. Some designs have circuits that keep the line-current harmonic distortion below 20% and provide a power factor in excess of 90%. Some ballasts also employ circuits to limit the current in-rush when power is applied to the ballast. This in-rush, which is a result of the electrolytic capacitors of an electronic ballast charging up, occasionally had been reported as a problem for switches and relays used to turn power to the ballasts on and off. Electronic ballasts also can be designed to operate with dc and low-voltage systems for applications in buses, airplanes, trailers, and battery-operated emergency systems. In addition, it has been reported that some T-5 and smaller fluorescent lamps have problems at the end of life in field applications. When a fluorescent lamp fails, typically one of the electrodes becomes an open circuit. This can create an asymmetric lamp current operating condition that can produce high local heating, which in turn can crack the lamp bulb or overheat and deform the lamp base. ANSI specifications for magnetic ballasts have been revised to address the end-of-life operation of these lamps.

2.3.4.2.3   Reduced-Wattage Ballasts.

Ballasts are available that operate standard lamps at 50 to 80% of their rated wattage. Energy-saving lamps should not be used in combination with these ballasts, since the arc will tend to waver.

2.3.4.2.4   Energy-Saving Ballasts.

Energy-saving ballasts have lower power losses than the more common magnetic ballasts. These may be rated by Certified Ballast Manufacturers (CBM) and are used either with common lamps or with reduced-wattage lamps. For example, power losses in two-lamp 40-W rapid-start ballasts have been reduced by 4 to 5 W per lamp over common magnetic ballasts. A typical two-lamp 40-W unit with a low-loss energy-saving ballast dissipates approximately 86 W, compared to approximately 95 W for most magnetic ballasts.

2.3.4.2.5   Energy-Saving Systems.

Specialized lamp-and-ballast combinations are available to achieve energy savings. These include a 32-W T-8 (4-ft) lamp with a high-efficiency ballast and a 28-W T-12 lamp, also with a high-efficiency ballast, having internal solid-state switches that turn off the usual rapid-start cathode heater voltage. These ballasts

can also operate a 34-W reduced-wattage lamp. Power reducers are also available for saving energy. These solid-state electronic devices are wired in series with the lamp ballast to reduce operating wattage. Note that a reduction in light output results.

2.3.4.2.6   Ballast Power Factor.

The power factor is defined as the ratio of input wattage to the product of root mean square (rms) voltage and rms current. It represents the amount of current and voltage that the customer is actually using as a fraction of what the utility must supply. High power factor is defined as being above 90%. A ballast with low power factor draws more current from the power supply and therefore, larger supply conductors might be necessary. Low-power-factor ballasts are more common with compact fluorescent systems than for 4-ft and 8-ft fluorescent systems. Some public utilities have established penalty clauses in their rate schedule for installations with low power factor. Some utilities require high power factor equipment.

2.3.4.2.7   Ballast Factor and Ballast Efficacy Factor.

The ballast factor is defined by ANSI (ANSI C82.2-1984)as the relative light output of a lamp operated on the ballast with respect to the same lamp on a reference ballast, usually expressed in percent.

2.4.   High-Intensity discharge lamps

High-intensity discharge (HID) lamps include the groups of lamps commonly known as mercury, metal halide, and high-pressure sodium. The light-producing element of these lamp types is a wall-stabilized arc discharge contained within a refractory envelope (arc tube) with wall loading in excess of 3 W/cm^2 (19.4 W/in.^{2}).

2.5.   Short-arc lamps

Short-arc or compact-arc lamps characteristically provide a source of very high luminance. They are primarily used in searchlights, projectors, display systems and optical instruments (e.g., spectrophotometers and recording instruments) and for simulation of solar radiation. They also can be used as sources of modulated light, generated through current modulation.

2.6. Miscellaneous discharge lamps

2.6.1. Low-Pressure Sodium Lamps

In low-pressure sodium discharge lamps, the arc is carried through vaporized sodium. The light produced by the low-pressure sodium arc is almost monochromatic, consisting of a double line at 589.0 and 589.6 nm. The starting gas is neon with small additions of argon, xenon, or helium. In order to obtain the maximum efficacy of the conversion of the electrical input to the arc discharge into light, the vapor pressure of the sodium must be approximately of 0.7 Pa (1/10−4 lb/in.^{2}), which corresponds to an arc tube bulb wall temperature of approximately 260°C (500°F). Any appreciable deviation from this pressure degrades the lamp efficacy. To maintain the operating temperature for this pressure, the arc tube is normally enclosed in a vacuum flask or in an outer bulb at high vacuum.

2.6.2. Glow Lamps

These are low-wattage, long-life lamps designed primarily for use as indicator or pilot lamps, night lights, location markers, and circuit elements. They range from 0.06 to 3 W and have an efficacy of approximately 0.3 lm/W. Glow lamps emit light having the spectral character of the gas with which they are filled. The most commonly used gas is neon, having a characteristic orange color. The glow is confined to the negative electrode. Glow lamps have a critical starting voltage, below which they are, in effect, an open circuit.

2.6.3. Zirconium Concentrated Arc Lamps, Enclosed Type

These lamps use a direct-current arc constituting a concentrated point source of light of high luminance, up to 45 million cd/m2. They are made with permanently fixed electrodes sealed into an argon-filled glass bulb. The light source is a small spot, 0.13 to 2.8 mm (0.005 to 0.11 in.) in diameter (depending on the lamp wattage), which forms on the end of a zirconium oxide-filled tantalum tube that serves as the cathode. The spectral power distribution is similar to that of a blackbody with a correlated color temperature of 3200 K. These lamps produce a candela distribution characterized by the cosine law. They require special circuits that generate a high-voltage pulse for starting and a well-filtered and ballasted

operating current. Suitable power supplies are recommended by the manufacturer.

2.6.4. Pulsed Xenon Arc (PXA) Lamps

These are ac xenon lamps with two active electrodes (a polarized xenon lamp has current flowing in only one direction and one active electrode). A switching reactor in series with the low-pressure lamp forces 50 to 100 peak amperes (120 pulses per second) through the lamp. The reactor also supplies a continuous current of 2 to 3 A to keep the lamp operating between pulses. The spectrum produced is characteristic of xenon, typically 6000 K. PXA lamps are available in linear and helical types. The efficacy of these sources is approximately 35 to 40 lm/W. Available lamp wattages range from 300 to 8000 W, and forced-air cooling is required during operation. PXA lamps are used in: the graphic arts industry for applications requiring instant start; high-intensity, stable light output; and daylight-quality color temperature.

2.6.5. Flashtubes

These light sources are designed to produce high-intensity flashes of extremely short duration. They are primarily used for photography; viewing and timing of reciprocating and rotating machinery; airport approach lighting systems, including navigation aids, obstruction marking, and warning and emergency lights; laser pumping; and entertainment applications.

2.6.6. Linear-Arc Lamps

Linear-arc quartz envelope lamps are available for both continuous wave and pulsed operation. Lamps operated in the pulsed mode are discussed above under flashtubes. Forced-air-cooled long-arc xenon lamps are made with arc lengths up to 1.2 m (4 ft), bore diameters up to 12 mm (0.47 in.), and wattages up to 6 kW. These lamps are used for special illumination requirements and solar simulation and have an efficacy of approximately 30 lm/W. They are used for UV photoexposure in the semiconductor and other industries. They are also finding use in the rapid thermal processing of silicon wafers.

2.6.7. Electroluminescent lamps

An electroluminescent lamp is a thin (typically less than 1.2 mm [0.05 in.]), flat-area source in which light is produced by a phosphor excited by a pulsating electric field. These lamps are used in decorative lighting, instrument panels, switches, emergency lighting and signs, and for backlighting liquid crystal displays (LCDs).

2.7. Light Emitting Diodes

2.7.1. AlInGaP and InGaN Light-Emitting Diodes

Aluminum indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN) are the two most common light emitting diode (LED) technologies, displacing older gallium arsenide phosphide (GaAsP), gallium phosphide (GaP), and aluminum gallium arsenide (AlGaAs) LEDs. The following is an overview of these technologies from the perspective of illuminating engineering.

2.7.2. Intensity and Color

Manufacturers commonly test and bin each LED for luminous intensity and color. Like incandescent reflector lamps, the luminous intensity of LED devices is specified in terms of its beam angle. Typically, all LEDs within a bin do not vary in luminous intensity by more than an factor of two. Because of the difficulty in measuring luminous intensity accurately, there is an expected 10% overlap between adjacent bins.

The color of an LED device is specified in terms of the dominant wavelength emitted, λd (in nanometers). Dominant wavelengths for the colors produced by AlInGaP and InGaN LED devices are plotted on the 1931 CIE chromaticity diagram, shown in Figure 2-20. AlInGaP LEDs produce the colors red (626 to 630 nm), red-orange (615 to 621 nm), orange (605 nm), and amber (590 to 592 nm). InGaN LEDs produce the colors green (525 nm), blue green (498 to 505 nm), and blue (470 nm).
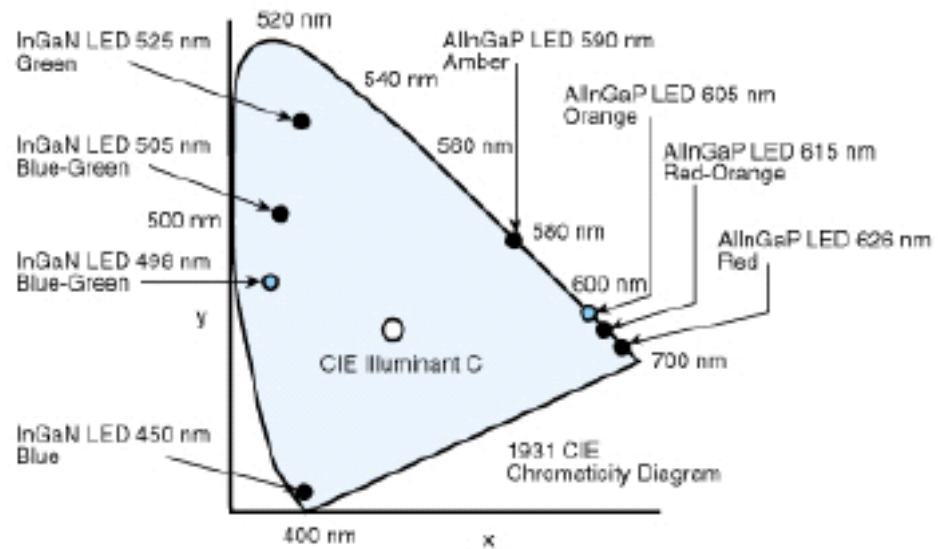
Figure 2-20 Dominant wavelengths, λd (nm), plotted on the 1931 CIE Chromaticity Diagram.

2.7.3.   Dimming

LEDs may be dimmed to 10% of maximum by reducing the drive current and still have even luminous intensity across an LED matrix. Pulse width modulation (PWM) is the preferred method for dimming LEDs. LEDs may be dimmed to 0.05% of maximum by using PWM. With PWM, the peak pulse current and the pulse rate remains constant while the duration of the on-time pulse is shortened.

2.7.4.   Reliability

The rated maximum junction temperature (TJMAX) is the most critical parameter on an LED device data sheet. Temperatures exceeding this value usually result in catastrophic failure of a plastic encapsulated LED device. TJMAX is actually a limitation related to packaging rather than to the LED chip. Lamp life for LED devices is based on the mean time between failures (MTBF). MTBF is determined by operating a quantity of LED devices at rated current in an ambient temperature of 55°C and recording when half the devices fail. Lumen depreciation for AlInGaP LED devices is shown in Figure 2-21. The dotted line is an extrapolation from currently available data. The same information for InGaN LED devices is shown in Figure 2-22. Fewer data are available for this

technology, and those data were collected at 25°C (77°F). The dotted line is extended for currently available data.
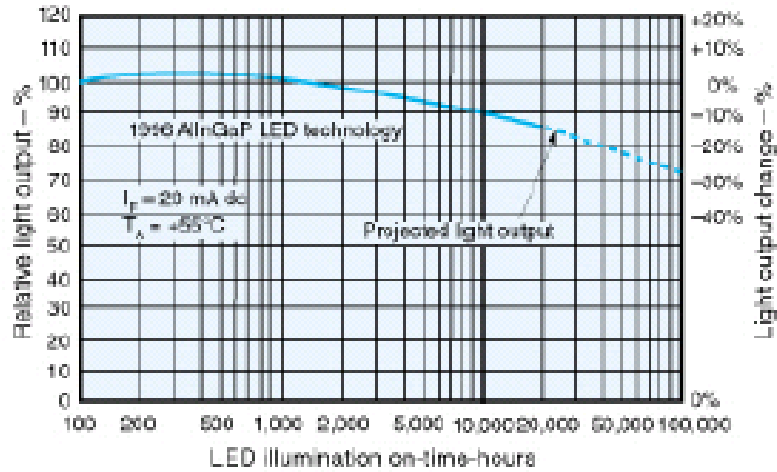
Figure 2-21 Projected long-term light output degradation for AlInGaP LED technology at 55¡C.
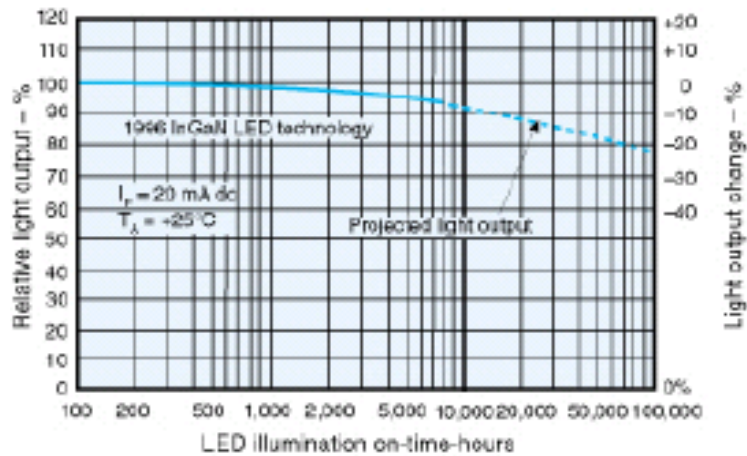
Figure 2-22 Projected long-term light output degradation for InGaN LED technology at 25¡C.

2.8.   Lasers

The word "laser" is an acronym for "light amplification by stimulated emission of radiation." Invented in 1960, a laser is a device that concentrates light waves on an intense, low-divergence beam. Even though the light source is an inefficient converter of electrical energy to light energy, a single laser becomes incredibly

efficient when applied to a very large-scale lighting requirement. Lasers are used in hundreds of different applications ranging from corporate theater and major concert tours to surveying and construction. Industrial business theater presentations use sophisticated laser graphics and animation to augment multi-image slide and video productions. Laser effects highlight or emphasize a corporate message or speaker with dramatic flair. Many large corporations use lasers at their conventions and special events. Performers have incorporated lasers in their performances and music videos.

2.9.   Carbon arc lamps

Carbon arc lamps were the first commercially practical electric light sources. They were used for many years in applications where extremely high luminance, high correlated color temperature, and/or high color rendering were necessary, such as in motion picture projection lamphouses and for theatrical followspots, searchlights, and film production daylight supplemental lighting. In most of those applications, xenon short arc and metal halide light sources have replaced carbon arc.

2.10.   Gas lights

Gaslights use gaseous fuels for light and decorative purposes. They use open gas flames or incandescent mantles of the upright and inverted types. For more information, see previous editions of the IESNA Lighting Handbook.

3.   Luminaires

A luminaire is a device to produce, control, and distribute light. It is a complete lighting unit consisting of the following components: one or more lamps, optical devices designed to distribute the light, sockets to position and protect the lamps and to connect the lamps to a supply of electric power, and the mechanical components required to support or attach the luminaire. This chapter provides information for both specifiers and manufacturers of luminaires. It describes most common types of luminaires, how they are used, and how their performance is evaluated, and gives a general classification system useful for understanding their application. With the exception of lamps (light sources), the characteristics, design, and manufacture of luminaire components are described.

3.1.   General Description

3.1.1.   Light Sources

Luminaires are designed and manufactured for all common types of electric lamps. Luminaires are commonly available for these lamps:

- Incandescent filament including tungsten halogen and infrared (heating) lamps

- Fluorescent

- Compact fluorescent

- Induction or electrodeless lamps, including fluorescent and sulfur lamps

- High-intensity discharge lamps, including metal halide, high-pressure sodium, and mercury

- Low-pressure sodium lamps

Luminaires are less common for xenon arc and carbon arc lamps. The size, materials, thermal properties, photometric performance, and power requirements of a luminaire depend on the type of lamp used. For example, lamps that produce a large amount of infrared (IR) radiation (heat) require luminaires that are vented

for convection, and fluorescent lamps that are sensitive to environmental temperature must be protected from low air temperatures.

3.1.2. Light Control Components

The lamps used in some luminaires have integrated light control components. These are usually incandescent and tungsten-halogen lamps with a reflective coating and/or refracting prisms on the bulb. These integral lamp components produce useful beams and patterns of light without any auxiliary optical control. In these cases, most of the light control is provided by the lamp; the luminaire is simply an appliance to hold the lamp, deliver electric power, and perhaps permit the lamp to be aimed in different directions. Most lamps emit light in virtually all directions, and their efficient application requires light control components to collect and distribute the light. Four types of light control components are commonly used: reflectors, refractors, diffusers, and louvers or shields.

3.1.2.1 *Reflectors.*

A reflector is a device, usually of coated metal or plastic, that has a high reflectance and is shaped to redirect by reflection the light emitted by the lamp. The surface finish of luminaire reflectors usually is classified as specular, semi-specular, spread, or diffuse. Some applications require the reflector to control the light very precisely, so specular or semi-specular reflecting material is used. Metal reflectors are formed and then polished or chemically coated to produce a specular finish. In some cases, metal reflectors are manufactured from metal stock that has already been treated to produce a specular finish. Plastic reflectors are molded and then coated with aluminum by vaporization. Examples of specular reflectors are those used to control the light from a metal halide lamp to produce a narrow beam of light for sports lighting, and the parabolic louvers in fluorescent lamp troffers. In some luminaires the reflector does not have to control the light very precisely, and it is sufficient for the reflector to have a high but nondirectional reflectance. An example of this is the white, slightly specular, coated metal reflectors in some large fluorescent lamp luminaires. On the other hand, diffuse reflectors have very little effect on the distribution of light and are uncommon in luminaires. Other applications and lamps require reflectors with special surface finishes, such as semi-specular or peened materials, or coatings to reduce color separation upon reflection (iridescence) when using certain

fluorescent lamps. Examples of reflectors are shown in Figure 3-1. In some cases, reflectors have properties varying with wavelength. Alternating layers of materials with differing indices of refraction are applied to glass. These layers have a thickness approximately that of the wavelength of light (500 nm). Interference effects produce reflection that changes with wavelength. This is useful if it desirable to reflect light but not reflect long-wavelength thermal radiation or, conversely, to reflect the long wavelength radiation and pass light. These reflectors are used when it is necessary to direct light and control the heat generated by the lamps.
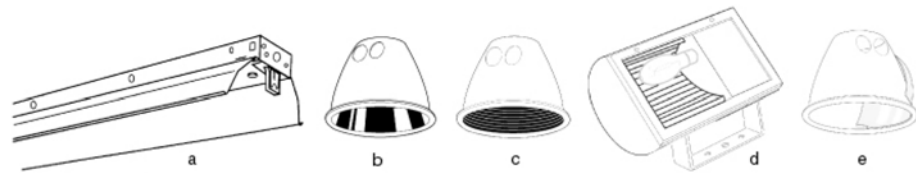
Figure 3-1 Examples of reflectors: (a) linear faceted, coated steel reflector in a strip fluorescent lamp luminaire, (b) and (c) spun specular and grooved aluminum reflectors for a compact fluorescent downlight luminaire, (d) faceted reflector for a floodlight luminaire, and (e) reflector with "kicker" to direct light for wall-wash luminaire.

3.1.2.2   *Refractors.*

Refractors are light control devices that take advantage of the change in direction that light undergoes as it passes through the boundary of materials of differing optical density (index of refraction), such as air to glass or air to plastic (Figure 3-2). A material, usually glass or plastic, is shaped so that light is redirected as it passes through it. This redirecting can be accomplished with linear (extruded, two-dimensional) prisms or with three-dimensional pyramidal-shaped prisms. These prisms can be either raised from the surface of the material or embossed into it. They are usually small enough to become a type of surface treatment on one side of an otherwise flat sheet of glass or plastic. The entire sheet is referred to as a prismatic lens. A collection of small prisms, acting in concert, can be used to control the directions from which light leaves a luminaire. This redirection can be used to partially destroy images and therefore to obscure lamps and reduce luminance by increasing the area over which the light leaves the luminaire. In some cases the sheet containing prisms is shaped to provide additional control. In specialized applications, such as the refractors used for some street lighting

luminaires, the prisms are on both surfaces of the material. Another application of refracting material takes advantage of total internal reflection. In this case the refracting material is shaped so that light passes into it through its first surface and mostly is reflected from the second surface back into the material and out the first surface. Some glass and plastic industrial luminaires use this type of light control. This is also the basis for the operation of light pipes and fiber-optic luminaires. For some luminaires, the lamp and application require a transparent cover to block ultraviolet (UV) radiation or prevent broken lamp components from falling out of the luminaire. Though providing little optical control, these cover plates often are referred to as lenses.
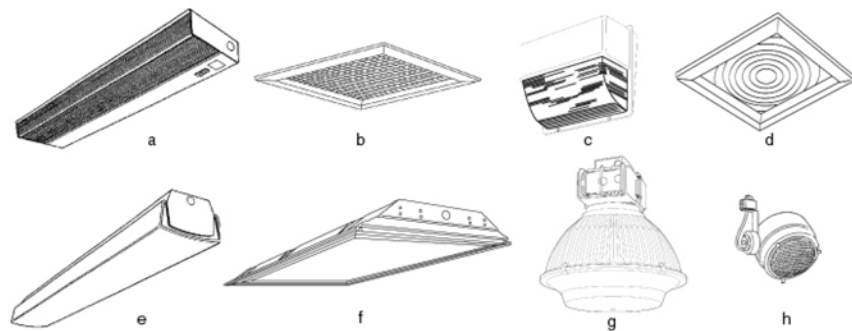
Figure 3-2 Examples of refractors: (a) prismatic lens on surface-mounted fluorescent lamp luminaire, (b) recessed luminaire with spread lens, (c) glass refractor on an outdoor area luminaire, (d) Fresnel refractor, (e) wraparound prismatic lens on a fluorescent lamp luminaire, (f) prismatic lens on recessed flourescent lamp luminaire, (g) low-bay industrial luminaire with prismatic refractor, and (h) track luminaire with spread lens refractor.

3.1.2.3   *Diffusers.*

Diffusers are light control elements that scatter (redirect) incident light in many directions. This scattering can take place in the material, such as in bulk diffusers like white plastic, or on the surface as in etched or sandblasted glass. Diffusers are used to spread light and, since scattering destroys optical images, obscure the interior of luminaires, suppress lamp images, and reduce high luminances by increasing the area over which light leaves a luminaire. Examples of diffusers are shown in Figure 3-3.
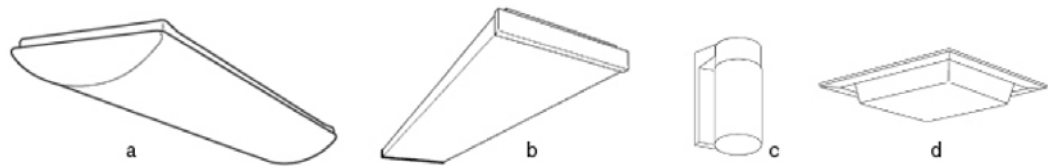
Figure 3-3 Examples of diffusers: (a) and (b) wrap-around white diffusers for fluorescent lamp luminaires, (c) jelly jar diffuser for compact fluorescent lamp luminaire, and (d) drop glass diffuser for metal halide lamp luminaire.

3.1.2.4   Shades, Shields, Louvers, and Baffles.

Shades and shields are opaque or translucent materials shaped to reduce or eliminate the direct view of the lamp from outside the luminaire Figure 3-4. Shades are usually translucent and are designed to diffuse the light from the lamp and provide some directional control. Blades, usually opaque and highly reflective, can be shaped and positioned to eliminate the direct view of the lamp from certain directions outside the luminaire and to control the direction from which the light leaves. If arranged in a rectangular grid, producing cells, they are called louvers. If arranged linearly they are called baffles. In large fluorescent lamp luminaires, louvers are designed so that the lamps are directly above the center of the cells formed by the louvers. In long narrow fluorescent lamp luminaires, baffles extend across the axis of the lamps. Louvers and baffles often are made of specularly reflecting metal, though some are of coated plastic. Though intended to eliminate the direct view of the lamp at some angles, specular louvers and baffles can provide lamp images at other viewing angles by reflection. In turn, these images may produce images in the screen of computer VDTs. See Figure 3-4 for examples of baffles and louvers.
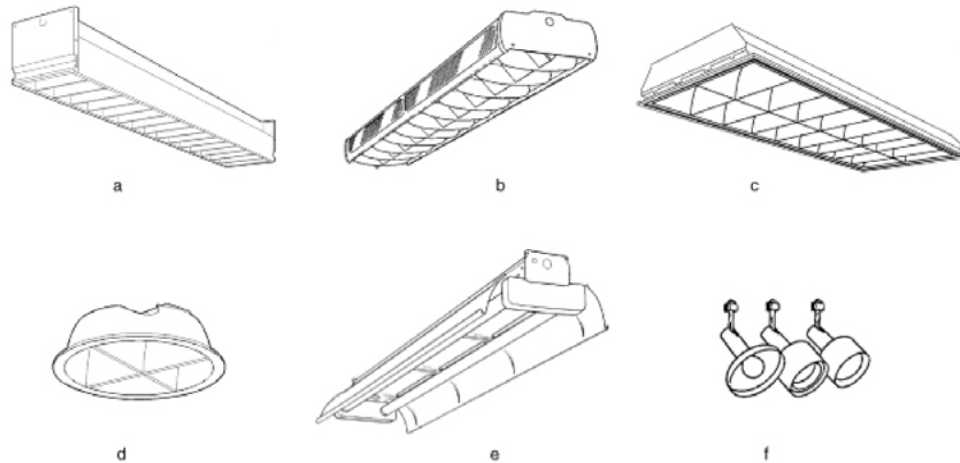
Figure 3-4 Examples of baffles, louvers, and shields: (a), (b), and (c) louvers for fluorescent lamp luminaires; (d) cross baffles for compact fluorescent lamp luminaires; (e) shield for industrial fluorescent lamp luminaire; and (f) hoods and cowls for track luminaires.

3.1.2.5   *Fiber-Optic Luminaires.*

A fiber-optic illumination system is a distributed lighting system allowing remote source illumination of areas and objects. A fiber-optic lighting system has a light source or illuminator, optical fiber, and various output fixtures selected to illuminate specific areas or objects. These systems can be used in lighting applications requiring the light source and light output to be separated, as in hazardous environments, wet locations, or in temperature-sensitive spaces. They also can be used when it is desirable to have sizes, shapes, or light output characteristics different from conventional luminaires. Virtually all of the IR and most of the UV radiation from lamps, as well as the electrical connections needed to power the system, are absent from the illuminated space. The separation of source from output allows the use of various components within the source enclosure that can provide interesting optical effects at the output. Such components can include color or effects wheels and filters.

3.1.2.6   *Mechanical components*

The mechanical components of a luminaire consist of a housing or general structure to support other components of the luminaire, and a mounting mechanism for the attachment of the luminaire to its support Figure 3-5. In some luminaires the reflector is a separate component that is attached to the housing, as in a compact fluorescent lamp downlight. In other luminaires, the housing

serves as the reflector, as in a fluorescent lamp troffer. If the luminaire uses a refractor or transparent cover, then hinged frames or doors often are provided to hold the lens. Access for cleaning and relamping is through this door. In damp or wet applications it is necessary to provide adequate seals to prevent migration of water into the luminaire. In some hazardous locations the housing and seals must keep explosive or flammable vapors from contact with high lamp surface temperatures or electric spark. These luminaires are said to be explosion proof. Many recessed luminaires are vented to dissipate heat that can degrade lamp performance. In some applications, the luminaire is used as part of the building's heating, ventilating, and air conditioning system. Air is supplied to or removed from the room using the luminaire. In this case, airways are provided within the luminaire as well as attachments for air ducts and slots through which air enters or leaves the room.
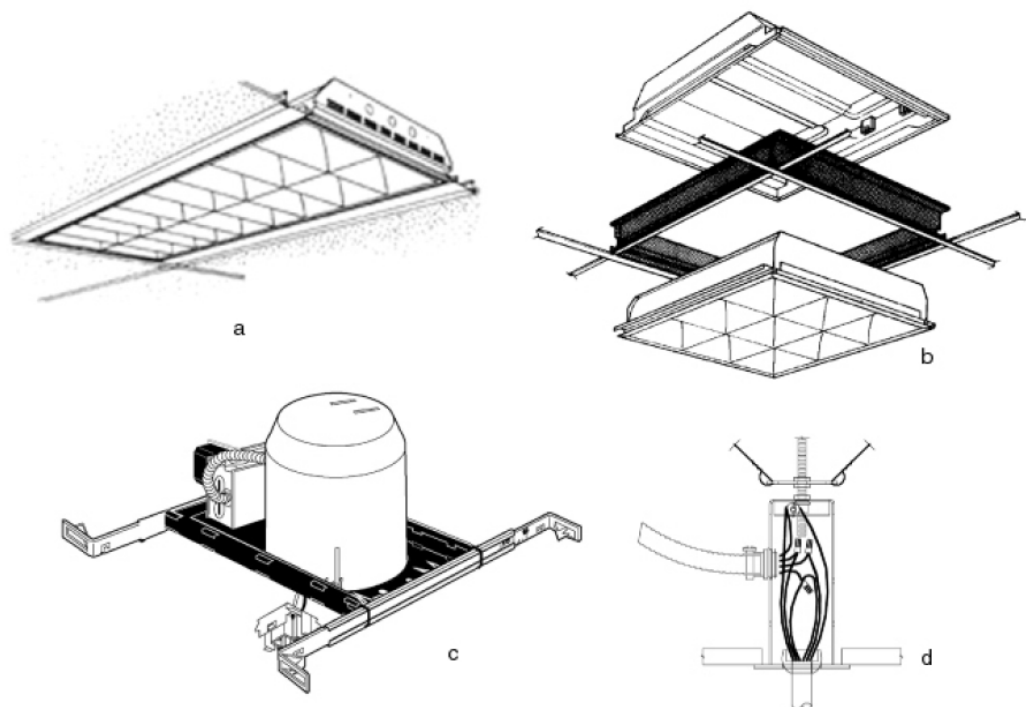
Figure 3-5 Examples of mechanical components of luminaires: (a) and (b) fluorescent lamp troffers showing housing and mounting to inverted-T ceiling system; (c) compact fluorescent lamp downlight showing housing, mounting for ballast, and mounting brackets; and (d) mounting and electrical connection for a pendant-mounted luminaire.

3.1.2.7   *Electrical Components*

If required, the luminaire contains and supports ballasts, starters, igniters, capacitors, or emergency lighting devices. The size and power handled by these components often determine the size of the luminaire and the requirements for proper thermal performance. In a few applications, these components are too heavy, too loud, or too large to be in the luminaire. In these cases, the ballast and other auxiliary equipment are mounted remotely from the luminaire and lamp. The luminaire also contains wiring and connectors to connect the lamp socket and, if present, the ballast to the external wiring that brings electrical power to the luminaire.

3.2.   Luminaire types and classification

3.2.1.   Purpose of Classification

Luminaire classification helps specifiers and manufacturers describe, organize, catalog, and retrieve luminaire information. The nature of luminaire classification has changed with the advance of computer and information technology. Modern lighting design and specification practice relies on computer-based luminaire databases, accessed on CD-ROM or over the Internet. This technology allows luminaire data to be updated frequently and easily. In such systems, a luminaire can be known by all of its characteristics, with any one being the path by which a search finds the luminaire in a database.

3.2.2.   Methods for Classification

Luminaires can be classified according to source, mounting, construction, application, and/or photometric characteristics. Classifications by application and photometric characteristics are discussed in the next two sections.

3.2.2.1   *Classification by Application.*

A common form of classification organizes luminaires by application. Many luminaire characteristics are determined by application, so this distinction proves useful in organizing luminaire information. Three application areas are usually distinguished: residential, commercial, and industrial. Within each application, luminaires can be classified by source, mounting, and con struction. Examples of these include residential ceiling-mounted room luminaires using incandescent

lamps, recessed fluorescent lamp troffer luminaires, and high bay suspended metal halide lamp luminaires.

3.2.2.2   *Classification by Photometric Characteristics.*

Another form of classification uses the luminous intensity or flux distribution of the luminaire. For luminaires used indoors, a method specified by the International Commission on Illumination (CIE) is commonly used.

3.2.2.2.1   The CIE Classification System.

The International Commission on Illumination provides a classification system based on the proportion of upward and downward directed light output. This system is usually applied to indoor luminaires.

- Direct lighting. When luminaires direct 90 to 100% of their output downward, they form a direct lighting system. The distribution may vary from widespread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed.

- Semidirect lighting. The distribution from semidirect units is predominantly downward (60 to 90%) but with a small upward component to illuminate the ceiling and upper walls.

- General diffuse lighting. When the downward and upward components of light from luminaires are about equal (each 40 to 60% of total luminaire output), the system is classified as general diffuse. Direct-indirect is a special (non-CIE) category within this classification, in which the luminaires emit very little light at angles near the horizontal.

- Semi-indirect lighting. Lighting systems that emit 60 to 90% of their output upward are classified as semi-indirect.

- Indirect lighting. Lighting systems classified as indirect are those that direct 90 to 100% of the light upward to the ceiling and upper side walls.

3.2.2.2.2   Indoor Luminaire Classifications By Cutoff.

There are several characteristics of indoor luminaire intensity distributions that are important for classification. This information can appear in the photometric report for a luminaire.

- Physical cutoff. The angle measured from nadir at which the lamp is fully occluded.

- Optical cutoff. The angle measured from nadir at which the reflection of the lamp in the reflector is fully occluded.

- Shielding angle. The angle measured from the horizontal at which the lamp is just visible.

3.3. Principal Types of Luminaires

3.3.1. Commercial and Residential

3.3.1.1 *Portable Luminaires*

These are completely self-contained luminaires designed to be moved and placed near the task to be lighted. They have a plug and outlet connection to electric power and usually contain integral switching and/or dimming. They usually contain low-wattage incandescent, tungsten-halogen, or compact fluorescent lamps.

3.3.1.2 *Furniture Mounted.*

Permanently attached to furniture or other equipment surface, these luminaires are designed to be in close proximity of the task and produce localized lighting. They can be found under kitchen cabinets and in bathroom vanities.

3.3.1.3 *Recessed Downlights.*

These are general-purpose luminaires designed to provide general or ambient lighting in a space. They are recessed into the ceiling and are designed to produce illuminance on a floor or workplane. Certain types have concentrated luminous intensity distributions designed for spaces with computer VDTs. It is often necessary to augment these luminaires with other types that raise wall luminances and add vertical illuminance to the space. Recessed downlights can be grouped by size. There are two types of recessed downlights. Incandescent, compact fluorescent, and metal-halide lamp downlights usually have modest apertures and can exhibit very low luminances at high viewing angles. Fluorescent lamp troffers use large fluorescent lamps and are usually used with a suspended tile ceiling system. Sizes range from 6 in. × 48 in. to 48 in. square.
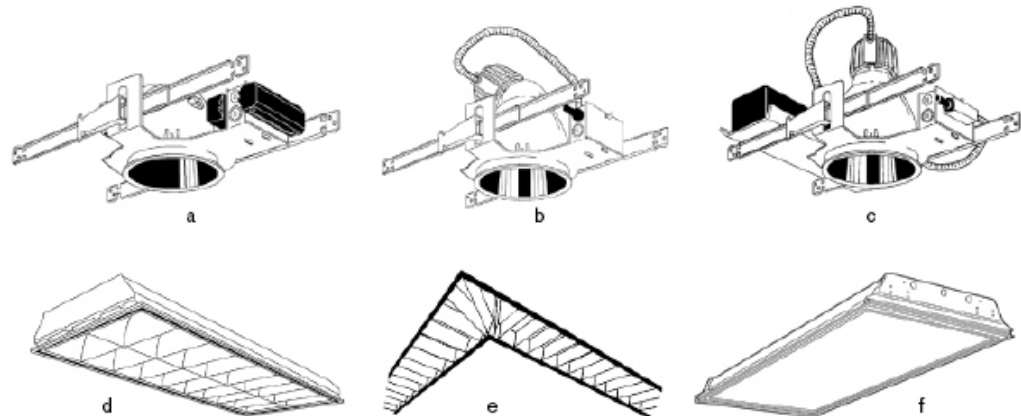
Figure 3-6 Examples of downlight luminaires using (a) compact fluorescent, (b) incandescent, and (c) metal halide lamps; (d) fluorescent lamp recessed troffer with parabolic louvers; (e) continuous linear; and (f) fluorescent lamp recessed troffer with prismatic lens.

3.3.1.4   Ceiling Surface Mounted.

These luminaires can provide general or ambient lighting with the addition that some of the light can be emitted upward to produce a higher ceiling luminance than recessed or surface-mounted downlights. Examples include fluorescent troffers, compact fluorescent downlights, incandescent and tungsten-halogen downlights for task lighting on kitchen counter tops, and wrap-around lens luminaires (Figure 3-7).
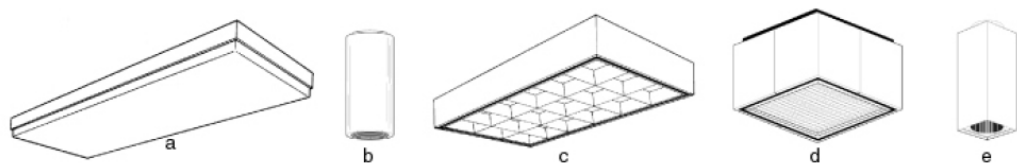
Figure 3-7 Examples of ceiling surface mounted luminaires; (a) wrap-around lens, (b) incandescent lamp downlight, (c) troffer, (d) metal halide lamp area light, and (e) metal halide lamp downlight.

3.3.1.5   Wall Washer.

These luminaires are used to produce a distribution of illuminance/luminance on a wall that, though not necessarily uniform, changes gradually from high values at the top of the wall to lower values down the wall. Many wall-wash luminaires are

designed to achieve an illuminance ratio from the top to the bottom of the wall of 10:1 or less. Wall-wash luminaires can be recessed or surface mounted. These can be grouped by size. There are two basic types of wall washers. Linear fluorescent wall washers usually have a reflector that allows them to be placed close to the wall, and are available recessed or surface-mounted. Other wall washers, including compact fluorescent, incandescent, halogen, or compact metal halide lamp luminaires, are smaller units that, if recessed, have a modest aperture and therefore can appear like other downlights in the space. They also can be surface mounted.

3.3.1.6   *Accent.*

These luminaires are either themselves ornamental or are designed to produce patterns of light that are ornamental. They can be ceiling recessed or surface mounted, or wall mounted. Ceiling-mounted accent luminaires use incandescent, tungsten-halogen, compact fluorescent, or low-wattage metal halide lamps. The lamps are adjustable or fixed. Sconces and other wall-mounted accent luminaires use incandescent, tungsten-halogen, or compact fluorescent lamps. Since they are often mounted low, they are often in the field of view, and therefore the designer should be aware of the potential for glare. Translucent shields, which vary in size or shape, are often used for lighting hallways, stairways, doorways, and mirrors. Wall-mounted luminaires with opaque shielding completely conceal the source from normal viewing angles and are strongly directional in light distribution. Downlight luminaires often are mounted on the wall for accent and display lighting, whereas uplight luminaires can be used for general, indirect lighting.

3.3.1.7   *Track.*

This refers to a system that includes luminaires and a track or rail that is designed to both provide mounting and deliver electric power. Track is generally made of linear extruded aluminum, containing copper wires to form a continuous electrical raceway. Some varieties can be joined or cut, and others set into a variety of patterns with connectors. Track is available in line or low-voltage, with remote transformers available for the low-voltage equipment. Track can be mounted at or near the ceiling surface, recessed into the ceiling with special housing or clips, or mounted on stems in high-ceiling areas. It also can be used

horizontally or vertically on walls. Mechanical considerations may limit certain mounting arrangements, particularly for wall-mounted installations. Track can be hardwired at one end or anywhere along its length. Flexibility can be added with a cord-and-plug assembly to supply power rather than with hardwiring. A variety of adjustable track-mounted luminaires are available for attachment at any point along the track. These luminaires come in many shapes and styles, housing a large assortment of lamps, including line and low-voltage. In addition, a number of luminaires are designed to create special effects for decorative applications. Track luminaires use incandescent, tungsten-halogen, compact fluorescent, metal halide, or high-pressure sodium lamps.

3.3.1.8   *Point Indirect.*

These luminaires are designed to provide general or ambient lighting by illuminating the ceiling with compact fluorescent, metal halide, or even high-pressure sodium lamps. They contain reflectors that help produce a wide distribution so that they can be mounted close to the ceiling. Pendants or cable usually suspends them, but some types are post-mounted from the floor.

3.3.1.9   *Linear Indirect.*

These luminaires are designed to use linear or compact fluorescent lamps to provide general or ambient lighting by illuminating the ceiling. Reflectors are used to produce wide distributions and permit short suspension distance. Linear indirect luminaires can be suspended from the ceiling by pendants or cable or, in the case of modest spans, mounted by their ends. They can also be mounted on the walls to form a perimeter lighting system. Suspended linear indirect luminaires usually have a luminous intensity distribution that is symmetric about the lamps' axis, whereas wall-mounted linear indirect luminaires typically have an asymmetric distribution.

3.3.1.10   *Linear Direct-Indirect.*

These luminaires are similar to the suspended indirect but provide some downward directed light. Variations are available for changing the proportion of upward and downward light.

3.4. Luminaire performance

Luminaire performance can be considered a combination of photometric, electrical, and mechanical performance. Photometric performance of a luminaire describes the efficiency and effectiveness with which it delivers the light produced by the lamp to the intended target. This performance is determined by the photometric properties of the lamp, the design and quality of the light control components, and to some extent any auxiliary equipment required by the lamp.

The electrical performance of a luminaire describes the efficacy with which the luminaire generates light and the electrical behavior of any auxiliary equipment such as ballasts. Luminaire efficacy is determined by lamp efficacy and, if present, the ballast and its interaction with the lamp. Electrical behavior, such as power factor, waveform distortion, and various forms of electromagnetic interference, are properties of the lamp and ballast.

The mechanical performance of a luminaire describes its behavior under stress. This can include extremes of temperature, water spray or moisture, mechanical shock, and fire.

3.4.1. Components of Photometric Performance

Luminaire photometric performance is summarized in a photometric report (**Errore. L'origine riferimento non è stata trovata.**). Luminous intensity values are determined from laboratory measurements and are reported as the luminaire's luminous intensity distribution. Electrical and thermal measurements are made and often reported. These include input watts, input volts, and ambient air temperature. In addition, some calculated application quantities are usually reported. These include zonal lumens, efficiency, and coefficients of utilization.
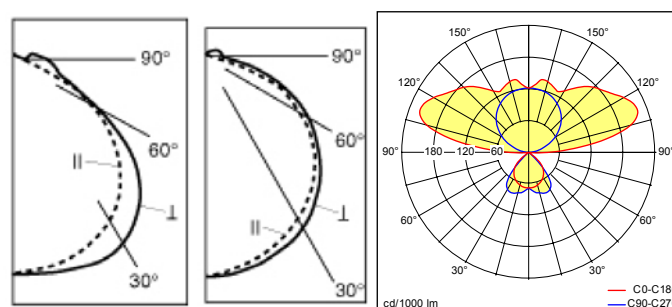
Figure 3-8 Data from an indoor photometric report

3.4.2. Effects of Luminaire Photometrics

3.4.2.1   *Luminaires and Their Lighting Effects.*

Luminaires light architecture, people, and visual tasks. Revealing architecture is often one of the most important purposes of lighting. Curves, coves, soffits, arches, vaults, coffers, and other architectural forms require light and shadow to be seen. A luminaire with the proper luminous intensity distribution is necessary for successful lighting in such cases.

Luminaires can produce patterns of light that are interesting and important to the appearance of the space being lighted. Scalloping, wall washing, and accenting are examples. A proper luminous intensity distribution is essential. Size of scallops, uniformity of wall washing, and sharpness of accenting depend on the distribution of the luminaire and to some extent on the lighted surface's texture and color.

Luminaires are also used to light visual tasks. The requirement for contrast and luminance determine the luminous intensity distribution and placement of luminaires. For direct lighting, computer VDTs usually require luminaires with a sharp cutoff luminous intensity distribution and very careful positioning if screen images are to be avoided. If sufficient contrast of glossy horizontal tasks is to be achieved, veiling reflections must be avoided. This requires light from the side. A luminaire with a wide luminous intensity distribution can be used to achieve this. The lighting effect produced by a luminaire is determined largely by its intensity distribution. Choosing the appropriate luminaire often means choosing the appropriate intensity distribution.

3.4.2.2   *Direct Lighting.*

The distribution may vary from widespread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed. Concentrated distributions can cause sharp shadows.

3.4.2.3   *Semidirect Lighting.*

The characteristics are essentially the same as for direct lighting except that the upward component tends to soften shadows and improve room brightness relationships. Care should be exercised with close-to-ceiling mounting of some

types to prevent overly bright spots directly above the luminaires. Efficiencies can approach and sometimes exceed those of well-shielded direct units.

3.4.2.4   *Direct-Indirect Lighting.*

Very little light is emitted at angles near the horizontal. Since this characteristic results in lower luminances in the direct-glare zone, direct-indirect luminaires are usually more suitable than general diffuse luminaires, which distribute the light almost equally in all directions.

3.4.2.5   *Indirect Lighting.*

In a well-designed installation the entire ceiling becomes the primary source of light, and shadows in the space are virtually eliminated. Also, since the luminaires direct very little light downward, both direct and reflected glare are minimized if the installation is well planned. It is also important to suspend the luminaires a sufficient distance below the ceiling to obtain reasonable uniformity of ceiling luminance without excessive luminance immediately above the luminaires.

3.4.2.6   *Semi-Indirect Lighting.*

The characteristics of semi-indirect lighting are similar to those of indirect systems except the downward component usually produces a luminaire luminance that closely matches that of the ceiling. However, if the downward component becomes too great and is not properly controlled, direct or reflected glare may result. An increased downward component improves the utilization of light over that for indirect lighting. This factor makes higher illuminances possible with fewer semi-indirect luminaires and without excessive ceiling luminance.

3.4.3.   Thermal Performance of Luminaires

In general, the thermal performance of luminaires cannot be isolated from the way in which they are used. In most interior applications and some exterior applications, luminaires are thermally coupled to their environment. However, there are some thermal issues that can be essentially isolated. Three of these are the effect of the luminaire on the operating temperature of the lamp, the effect of lamp heat on luminaire materials, and the effects of air handling.

3.4.3.1 *Lamp Operating Temperature.*

The performance of many lamp types is dependent on the bulb wall temperature. This is particularly true for fluorescent lamps, for which both light output and electrical power input--and thus luminous efficacy--vary with the temperature of the coldest spot on the bulb wall. The lamp temperature in turn is a function of the heat balance between the lamp and its surroundings. Electrical energy provided to the lamp is partly converted into light, the balance being dissipated through the mechanisms of thermal (infrared) radiation, convection, and conduction.

Even the most efficient lamps convert only a moderate percentage of their electrical power input into visible light. The efficacy varies from a low of 10% for incandescent lamps, to approximately 19% for fluorescent lamps, to a high of 28% for low-pressure sodium lamps. With the exception of low-pressure sodium lamps, the greatest percentage of energy converted by most lamps is dissipated as infrared radiation. The relative energy dissipation by convection and conduction depends on airflow conditions and the temperature around the lamp, and on the details of the lamp mounting and luminaire design.

3.4.3.2 *Effects on Luminaire Materials.*

Since lamps emit energy at infrared as well as visible wavelengths, it is useful to examine the radiant properties of materials used in luminaires. The transmittance and reflectance of most materials are wavelength dependent. Thus, for example, a lens material can be selected that has high visible transmittance but low infrared transmittance, thereby reducing the amount of heat radiated from the luminaire. However, the heat that is trapped in the luminaire causes the lamp temperature to be greater than it would be otherwise. This may be desirable if higher lamp temperatures are needed to boost efficiency, but consideration should be given to the possibility of increased thermal stresses within the luminaire. Figure 3-9 lists the radiant properties of several materials that are commonly used in lighting systems, including the percentage reflectance and transmittance at selected wavelengths.

Material	Visible Wavelengths						Near Infrared Wavelengths						Far Infrared Wavelengths							
	400 nm		500 nm		600 nm		1000 nm		2000 nm		4000 nm		7000 nm		10,000 nm		12,000 nm		15,000 nm	
	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T
Specular aluminum	87	0	82	0	86	0	97	0	94	0	88	0	84	0	27	0	16	0	14	0
Diffuse aluminum	79	0	75	0	84	0	86	0	95	0	88	0	81	0	68	0	49	0	44	0
White synthetic enamel	48	0	85	0	84	0	90	0	45	0	8	0	4	0	4	0	2	0	9	0
White porcelain enamel	56	0	84	0	83	0	76	0	38	0	4	0	2	0	22	0	8	0	9	0
Clean glass-3.2 mm (0.125 in.)	8	91	8	92	7	92	5	92	23	90	2	0	0	0	24	0	6	0	5	0
Opal glass-3.9 mm (0.155 in.)	28	36	26	39	24	42	12	59	16	71	2	0	0	0	24	0	6	0	5	0
Clear arcylic-3.1 mm (0.120 in.)	7	92	7	92	7	92	4	90	8	53	3	0	2	0	2	0	3	0	3	0
Clear polystyrene-3.1 mm (0.120 in.)	9	87	9	89	8	90	6	90	11	61	4	0	4	0	4	0	4	0	5	0
White arcylic-3.2 mm (0.125 in.)	18	15	34	32	30	34	13	59	6	40	2	0	3	0	3	0	3	0	3	0
White polystyrene-3.1 mm (0.120 in.)	26	18	32	29	30	30	22	48	9	35	3	0	3	0	3	0	3	0	4	0
White vinyl-0.76 mm (0.030 in.)	8	72	8	78	8	76	6	85	17	75	3	0	2	0	3	0	3	0	3	0

Measurements in the visible range were made with a General Electric recording spectrophotometer. The reflectance was measured with a black velvet backing behind the samples. Measurements at 1000 and 2000 nm were made with a Beckman DK2-R spectrophotometer. Measurements at wavelengths greater than 2000 nm were made with a Perkin-Elmer spectrophotometer. Reflectances in the infrared region are relative to evaporative aluminum on glass.

Figure 3-9 Properties of Materials Used in Luminaires (T = Percent ransmittance and R = Percent Reflectance at the Selected Wavelength).

3.4.3.3 *Air Handling.*

The thermal performance of an indoor luminaire can also include its ability to deliver or extract air from a space. These heat-transfer luminaires often are referred to as air-handling luminaires and are constructed to add or remove heat from a space by moving air. They are constructed to minimize the effect of the air on the lamp bulb temperature.

3.4.4. Testing and Compliance

Luminaires should be installed in accordance with regional safety regulations and be certified for safety by an organization that is accredited in the region in which the luminaire is installed. National and local electrical codes sometimes determine the type of lighting equipment that can be used and the method of installation. Typically, luminaires are tested in accordance with national or international safety standards. These establish a minimum level of safety to reduce the likelihood of fire or electric shock.

4.   State of the art

Members of the lighting community have long speculated about the effects of lighting quality on human performance, comfort, and well-being. This debate has become particularly heated as energy conservation has increased in importance and building energy codes have reduced the power available for lighting. Past attempts to develop a metric for lighting quality, even in the limited case of office lighting, have largely failed. One important reason for this failure is poor science: poor research design, statistical analysis, and reporting. The limitations include the use of abstract tasks for visibility measurements, a narrow range of behavioural outcomes, and inadequate specification of the population to which the data apply. This paper proposes that lighting quality research be recognised as a subset of environment-behaviour research and presents a behaviourally-based definition of lighting quality. Selected examples from the lighting literature that fall within this definition are reviewed. Adherence to the common practices of the behavioural sciences promises improved knowledge of lighting effects on behaviour that researchers can bring to interdisciplinary discussions for consensus-based lighting design recommendations.

4.1.   Determinants of Lighting Quality

Lighting quality may be the most-talked-about but least-understood concept in lighting research and lighting design. Interest in lighting quality is currently high, judging from the occurrence of sessions and workshops at almost all major conferences (e.g., at the Commission Internationale de l'Éclairage session in New Delhi, India, in November 1995; at the Chartered Institute of Building Services Engineers 1996 National Lighting Conference in Bath, England, in March 1996; and at Lightfair International in San Francisco, May 1996). The introduction of building energy codes and pressure to increase energy-efficiency has re-opened an old debate.In the mid-1970s, as the energy crisis peaked and efforts to conserve energy mounted, the lighting community began to express its fear that the quality of the lit environment would decline with reductions in lighting energy use (e.g., Benya & Webster, 1977; Begemann, 1983; Chase, 1977; Florence, 1976). In the 1980s, the Illuminating Engineering Society of North America (IESNA)-sponsored Illumination Roundtables called for more research

into both subjective and objective measures of lighting quality ("Illumination Roundtable III", 1984). This led to a massive study, monitored by the Oak Ridge National Laboratory, co-sponsored by the Lighting Research Institute, the Electric Power Research Institute, the New York State Energy Research and Development Authority, and the U.S. Department of Energy, and conducted by the American Institute of Architects Foundation and the Institute for Social Research at the University of Michigan. The initial report of this undertaking to measure both photometric conditions and occupant ratings of lighting quality totalled four volumes (e.g., Marans & Brown, 1987) and a fifth volume, a re-analysis, was issued in 1989 by the National Institute for Standards and Technology (Collins, Fisher, Gillette, & Marans, 1989). Nonetheless, the IESNA Quality of the Visual Environment committee reported in 1994 that it was beginning "the process of identifying factors that contribute to lighting quality" (Miller, 1994, p. 20).

One of the few points of agreement is that quality differs from quantity. Many share the definition that lighting quality is "a term used to describe all of the factors in a lighting installation not directly connected with quantity of illumination" (Stein, Reynolds, & McGuinness, 1986, p. 887; cf. Wagner, 1985). The appropriate quantity of light contributes to the achievement of good quality, but is not its sole determinant. Other dimensions, including illuminance uniformity, luminance distributions, spectral power distribution, and glare are potential contributors to overall lighting quality (cf. Collins, 1994; Boyce, 1987; Miller, 1994). What is "appropriate" depends on the setting, activities, aesthetics, and other human needs in the space, including safety and security. Furthermore, the characteristics of the people who will use or experience the space also influence whether on not the lighting installation will achieve good quality (Boyce, 1983; Brundrett, 1983). Thus, determination of lighting quality in any individual case will require information about the setting and the activities to be undertaken there; the actors in that setting; and, the luminous conditions provided there.

Some writers are pessimistic about the search for predictors of lighting quality: "It may be impossible to establish criteria that ensure effective orientation and provide adequate visibility for the varying needs of work, play, and understanding" (Erhardt, 1994, p. 9). Certainly, there have been attempts to do so: equivalent sphere illuminance, visual comfort probability, and, arguably, visual performance models, are some approaches that have been undertaken to aid the

determination of appropriate luminous conditions. This paper reviews previous approaches to predicting good lighting, explores the underpinnings of the concept of lighting quality, and presents a model for the study of lighting quality founded on the principles of behavioural science.

4.2.   Attempts at Lighting Quality Indices

Although not described as indices of lighting quality, there have been several attempts to provide numerical guidance to lighting designers and specifiers so that adequate lighting conditions would be achieved. Some, such as equivalent sphere illuminance, were primarily indices of quantity, rather than quality per se; others, notably visual comfort probability, addressed quality but in a limited way.

4.2.1.   Visibility Level (VL) and Equivalent Sphere Illuminance (ESI)

Visual performance as the key outcome for lighting design inspired Blackwell's visibility level model (Blackwell, 1959), which was adopted by the International Commission on Illumination (CIE) (CIE, 1972). Each task was to be compared to a reference task to determine its visibility in terms of revealed contrast. The reference task is the detection of a luminous disc subtending 4 min of arc, viewed for 1/5 sec. By exposing subjects to a broad range of background (adaptation) luminances, it was possible to obtain a standard visual performance curve (relative contrast sensitivity, RCS) relating threshold contrast to background luminance (Blackwell, 1959). The standard curve used in the visibility model was constructed from a population of 20-30-year-olds with normal or corrected-to-normal vision, and the reference illumination is diffuse white light with colour temperature of 2850 K. Visibility level was calculated as the ratio of the threshold contrast of the task to the threshold contrast of the standard luminous disc, which was determined using a special device, the visibility meter. The VL thus calculated represents visibility under very special conditions. The light was unpolarised, diffuse, of a particular colour temperature, and produced with uniform luminance at all parts of the task. The CIE visual performance model attempted to correct for these special conditions by the use of multiplying factors (CIE, 1972; Levy, 1978).These multiplying factors were the contrast rendering factor (CRF), the disability glare factor (DGF), and the transient adaptation factor (TAF). In effect, the multiplying factors were an attempt to produce an index that combined the quantity and quality of illumination. CRF is an index of the effects of the polarisation, spectral composition, and spatial pattern of the actual lighting

installation on task visibility, in comparison to the reference lighting conditions; ultimately, it was an index of the effects of veiling reflections in reducing task contrast. DGF captured the effects of the pattern of luminances in the task environment to either enhance or reduce visual performance potential in comparison with the reference lighting. TAF measures the loss in contrast sensitivity that occurs when the luminous environment is markedly nonuniform, so that the eye must frequently adapt to different levels of brightness as the gaze shifts. These values, calculated from photometric data from the actual lighting installation or from a visibility meter, are used to calculate the effective visibility level (VL_{EFF}): $VL_{EFF} = VL \times CRF \times DGF \times TAF$. VL_{EFF} was to be used as an index for comparing different luminous environments; the higher its value, the better the lighting (Levy, 1978). However, simple means to measure DGF and TAF were never developed, leaving no way to calculate this index outside a laboratory.

A new concept was developed in the 1970s to provide guidance to lighting specifiers without resort to a visibility meter (Committee on Recommendations for Quality and Quantity of Illumination [RQQ], 1970): Equivalent Sphere Illuminance (ESI). ESI is "the level of sphere illumination which would produce task visibility equivalent to that produced by a specific lighting environment" (Kaufman & Christensen, 1989, p. 14).

Again, the goal was a way to specify both quantity and quality using a single value to describe the lighting requirement for a given task (e.g., high-contrast back-on-white print). One would need to know the adaptation luminance, the CRF, the Luminance Factor (conceptually, this is the task reflectance), and to have the RCS curve handy. Given the adaptation luminance, one determines the RCS from existing data, multiplies it by the CRF for the given installation to obtain the effective relative contrast sensitivity (RCS_{EFF}). One then would read the required adaptation luminance for that RCS_{EFF} from the RCS curve, and divides this luminance by the luminance factor to obtain the required ESI.
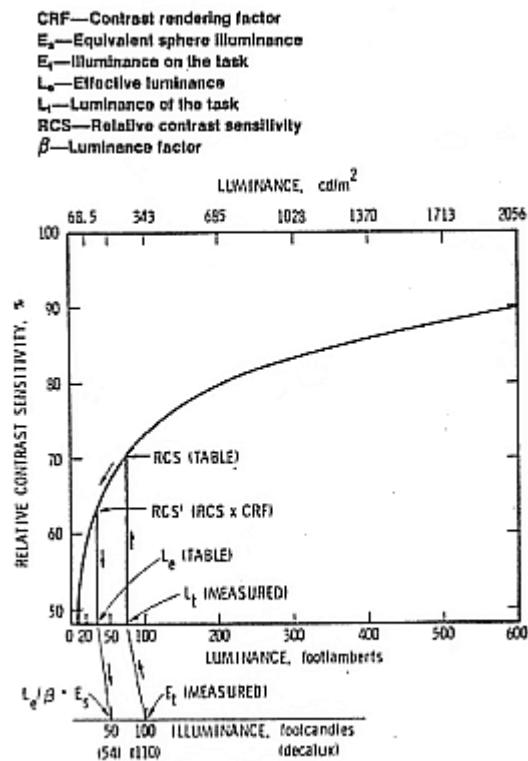
Figure 4-1. Graphical method of obtaining ESI. Beginning with the task illuminance and following the arrows, one can determine the ESI for a given task. Reprinted from Rea (1984).

Figure 4-1 summarises the graphical method of obtaining ESI. When existing visual performance data were plotted against VL, it became apparent that visual performance did not increase appreciably for VL values greater than eight. Therefore, this was adopted as the design standard (CIE, 1972). At this time, illuminance recommendations were to be based on the importance of the task (a rough estimate of the consequences of errors); the difficulty of the task, and the age of the viewer; these conditions modified the visibility level of the task and, consequently, the required ESI to achieve the target VL of eight. The system was sufficiently complex that lighting specification was said to become the purview of the vision specialist (Dorsey & Blackwell, 1975). As a derived value, ESI had several drawbacks (Boyce, 1978; Rea, 1984). Although it was based upon visibility data, these data did not represent the visual tasks people typically perform. People generally look at objects with features from which the visual system constructs meaning (for example, faint faces or letters), rather than luminous discs than convey no information. Also, the data assumed that all viewing is static and on-axis, whereas we obtain much information from the

periphery of the visual field, and often view moving objects. Strong objection also emerged to the assumption that the RCS curves, based on the threshold of detection, characterised the visibility of highly visible objects (suprathreshold visibility) (Ross, 1978). A further problem, seldom mentioned in the literature, is the limited range of reference tasks for which CRF curves were developed. In fact, from the literature on ESI one could be forgiven for forgetting that CRF is specific to a given task (e.g., pencil writing on white paper). Further CRF data for widespread application to other kinds of tasks was never available. For all of these reasons, ESI never became a formal part of the IESNA consensus-based illuminance recommendations (e.g., IESNA, 1981, 1987).

4.2.2.   **Visual Comfort Probability**

Whereas the VL and ESI systems were based principally on visual performance, visual comfort probability (VCP) was developed to address discomfort glare, a psychological phenomenon (RQQ, 1966). The experimental work predicts discomfort glare ratings (DGR)s from luminous conditions: source luminance, luminances in the field of view, the visual size of the glare source, and the location of the glare source in the field of view (Figure 4-2). The DGRs are converted to the probability that a population of viewers will consider that sensation acceptable. In a given geometry along a specified line of sight, a luminaire with a VCP of 80 will produce acceptable glare sensations in 80% of the population. Standard conditions were adopted for the calculation of VCP, and a consensus developed that a luminaire with a VCP of 70 is acceptable (IESNA, 1981, 1987; Rea, 1993). Neither ESI nor VCP alone were developed as a complete specification of lighting quality: ESI addressed quantity and veiling reflections from a visibility standpoint, and VCP addressed discomfort glare. Herst and Ngai (1978) suggested that the two values be combined to give a value they called a Lighting Quality Index (LQI). The LQI was to be calculated on the basis of VCP and ESI maps of a space: LQI is the percentage of the space meeting the minimum criteria for both VCP and ESI. Individuals were free to set their own criteria for both VCP and ESI, so the LQI for any space might depend on the limits set by the designer. Although this approach was intuitively attractive to some, it never gained a wide following, probably because of the problems inherent in the ESI system. Several features of the VCP model limit its applicability as an indicator of discomfort glare.
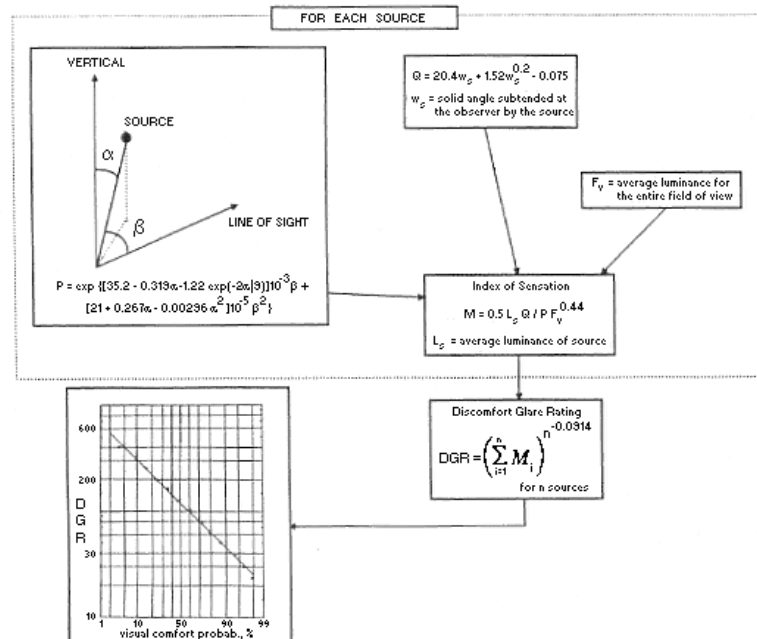
Figure 4-2. Derivation of Visual Comfort Probability (VCP) from luminance data and lighting system geometry.

The original model was developed using flat-bottomed recessed luminaires only, and initially was restricted to that application (RQQ, 1966). The validity of the curves for the wide range of luminaires and possible installations is unknown. That is, the model only makes predictions for a given line of sight, and probably does not hold for other viewing positions that occupants might reasonably adopt; data to test this hypothesis are scanty. Furthermore, evidence shows that perceptual differences exist between uniform and nonuniform sources that render the VCP model ineffective in predicting glare ratings for nonuniform sources (Waters, Mistrick, & Bernecker, 1995). A more serious, but rarely discussed, limitation is the original behavioural data on discomfort. The initial VCP data were collected from a total of 200 individuals in the Midwestern U.S. in the 1960s (cited in RQQ, 1966). The Lighting Handbook discussions of VCP have never specified the characteristics of this sample, and have never included limitations on the types of occupant populations to which VCP values can reasonably apply (e.g., Rea, 1993). However, we know that there are persistent cultural differences in illuminance preferences (e.g., Belcher, 1985) and evidence suggests that other individual differences also affect lighting level preferences (Heerwagen, 1990). Therefore, we have good reason to believe that the original DGR data from which

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VCP was developed might not be comparable to the perceptual glare experiences of other people in other places, and we have no information about the applicability of these data to glare from contemporary light sources.

4.2.3. Comfort, Satisfaction, and Performance (CSP) Index

The CSP index was developed to predict the likelihood that office workers will be satisfied with the visual environment provided for them (Bean & Bell, 1992). It is conceptually similar to the VCP system in this sense. However, its development followed a different path. Figure 4-3 summarises the calculation of CSP.
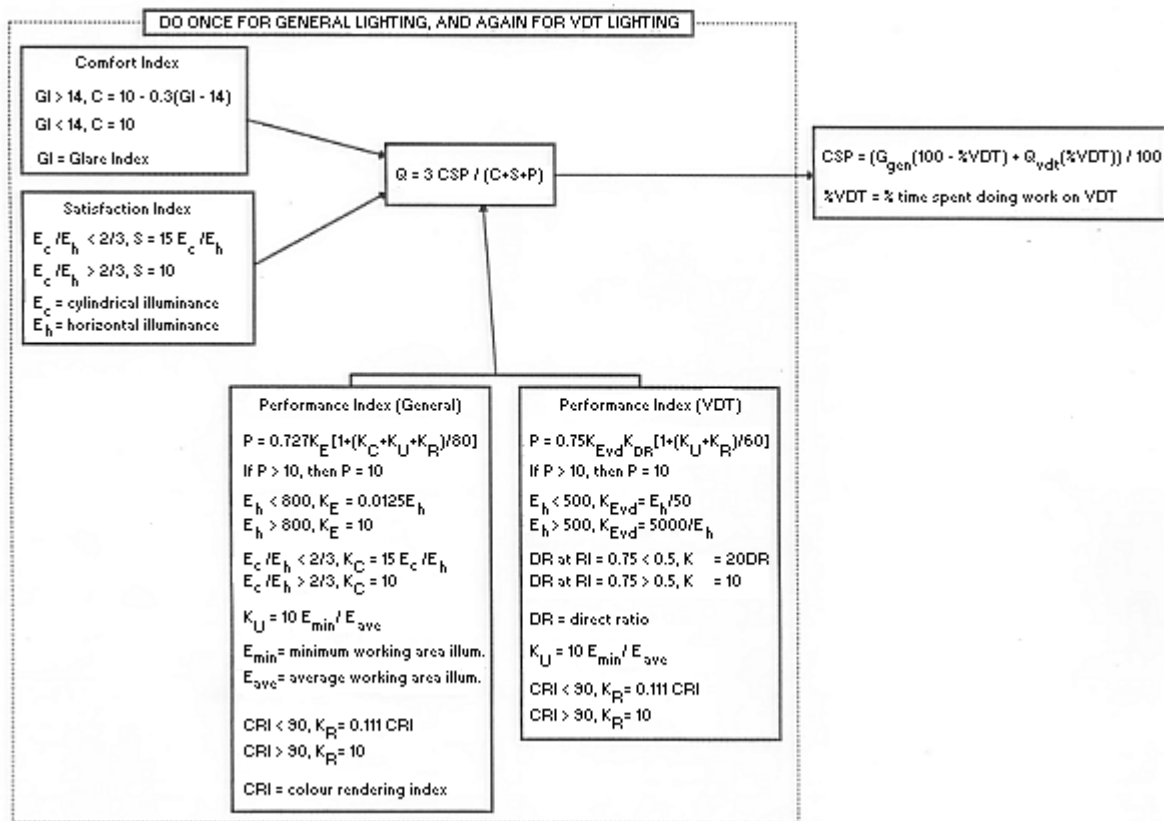
Figure 4-3. Derivation of the CSP Index from photometric data (adapted from Bean & Bell, 1992).

Bean and Bell developed their equations for the predictors from existing knowledge and codes. Thus, their comfort index is based solely on the glare index; satisfaction is predicted from cylindrical and horizontal illuminance. Performance is derived from horizontal and cylindrical illuminance, illuminance uniformity, and colour rendering, using criterion conditions for each that are

derived from practical experience and existing codes. Comfort, satisfaction, and performance are each accorded equal weight in calculating the CSP index, in the absence of any data or community agreement that it should be otherwise.

This approach is reasonable, given current knowledge, and the authors acknowledged that further development, validation, and refinement would be necessary (Bean and Bell, 1992). Bean and Bell reported only that the rank correlation coefficient between calculated CSP values and ratings on an analogue scale of lighting acceptability was 0.54 (p<.01). This is the best correlation they could achieve by altering the terms of the CSP model; because the model was altered to fit the data, it does not constitute an appropriate independent test of the model.

However, the utility of CSP has come into question in light of recent results. Perry, McFadden, Carter, & Manzano (1995) attempted to replicate Bean and Bell (1992). They obtained a very low correlation between the subjective ratings of lighting acceptability and the photometrically derived CSP index. That is, in this sample, the CSP index did not predict the occupants' judgements as well as in the original sample. Perry et al. were unable to determine precisely which parameters of the lit environment would provide better predictive power, but argued that closer examination of the influence of individual parameters on occupants' responses will be required for the development of a lighting quality assessment method.

4.2.4. Visual Performance Models

Strictly speaking, contemporary visual performance models address only the quantity-of-illumination issue. For example, the relative visual performance model (RVP) was developed in order to overcome deficiencies in previous models of visual performance, including the visibility level model, for the purpose of improving illuminance level recommendations (Rea, 1986a, 1986b, 1987). RVP describes suprathreshold visual performance in terms of target contrast, size, and adaptation luminance and includes modifiers for viewers of varying ages between 20 and 65 years (Rea & Ouellette, 1991; see Figure 4-4). Bailey, Clear, and Berman (1993) have presented an alternative model that emphasises visual size rather than contrast.
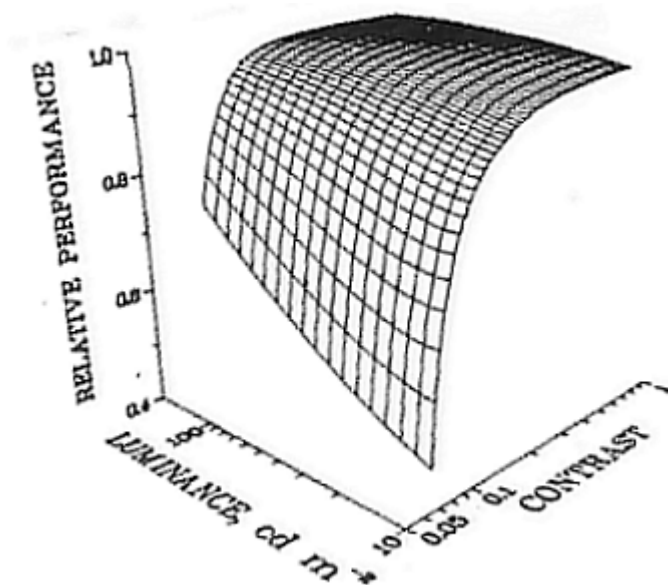
*Figure 4-4 Graphic representation of the Relative Visual Performance model
(Rea & Ouellette, 1991).*

Boyce (1995a) observed that these models are remarkable more for their similarities than their differences. The visual performance models consistently show that the visual system can sustain performance over a wide range of conditions, but that at some point the conditions become too severe and visual performance rapidly deteriorates. As Boyce stated, "To put it bluntly, what this means is that for many visual tasks, lighting is unimportant to visual performance" (Boyce, 1995a, p. 7-8).

Although the goal for visual performance modellers has been to create an empirically-based system for illuminance specification, all practical illuminance decisions reflect more than one task, must be suitable for viewers of varying ages, and must also satisfy more complex and subtle needs than vision alone. Illuminance decisions therefore go beyond the purview of any conceivable visual performance model. That is, providing good-quality lighting is not a matter only of providing an adequate quantity of light.

One striking feature of the scientific and lighting literature as it relates to lighting quality is that although the outcomes it seeks to explain are behavioural (e.g., discomfort, performance, perception), there is seldom any mention of current behavioural science; likewise, behavioural scientists with similar interests rarely cite the lighting literature. For example, in 1995 a lengthy review paper on visual

performance in a major journal, Psychological Review, did not cite any of the lighting literature on the topic (Smith, 1995). Nor is the literature cited by Smith among the common references cited by lighting researchers. If progress is to be made on the understanding of lighting quality, then this communications impasse must be broken, and behavioural science explicitly incorporated into lighting research.

4.3. A Behavioural Definition of Quality

4.3.1. Lighting in Environment-Behaviour Research

The assumption underlying the desire to understand lighting quality is that improved lighting quality will provide payoffs for the occupant who uses the installation, for the purchaser of the installation, and to the various members of the lighting industry who design, specify, and manufacture the lighting system. The suggestion that improved lighting quality could improve productivity is particularly popular in the trade literature (e.g., Kiernan, 1994; Shepard, 1986; Taylor, 1980), and this economic motivation underlies much lighting research. Interest in providing conditions conducive to productive work is also a fundamental element in environment-behaviour research concerning workplaces (e.g., Baron, 1994; Sundstrom, 1986).Baron (1994) presented a conceptual model for the study of relationships between physical conditions, personal characteristics, and individual and group outcomes. An adaptation of this model is presented in Figure 4-5.
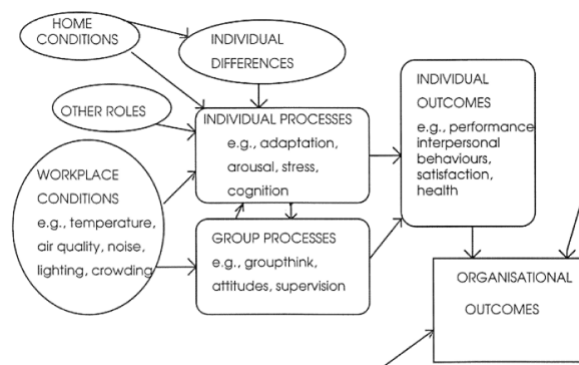
Figure 4-5 Conceptual model of work-related relationships studied by environment-behaviour researchers (after Baron, 1994).

The final outcomes of interest occur at two levels: individual performance, health, and general well-being; and organisational outcomes, which can include customer satisfaction, employee turnover and the bottom line, profit or loss. The unlabelled arrows to these outcomes represent inputs that lie outside the purview of environment-behaviour research: for example, the costs to provide the workplace; regulatory constraints on the organisation; or, the state of the economy.

The model proposed here bears some similarity to a model presented at the CIE session in Kyoto (Hayward & Birenbaum, 1979), which appears to have had little effect on lighting research. That model, like this one, focuses on the behaviour of the people in a space as the outcome that the design process seeks to influence. The model in Figure 5 is proposed as an organising tool for lighting-behaviour research, as part of environment-behaviour research in general. Lighting's place within the context of the whole environment is an important consideration, as it has long been known that environmental stressors interact in ways that cannot be predicted from their individual effects (Wilkinson, 1969). For more detailed information about environment-behaviour research on workplaces, consult Baron (1994), Evans and Cohen (1987), Sundstrom (1986), and Wineman (1986).

Ellis (1986) implicitly used this model in discussing three case studies of lighting design projects. His evaluations of the projects, also not systematic from a scientific point of view, were comprehensive in including the effects of the lighting changes on task visibility, glare ("functional" effects), indirect effects on mood in relation to the appearance of the space ("aesthetic" effects), and effects on attitudes related in part to the participatory design and evaluation process ("symbolic" effects). The attitude shifts, he reported, facilitated occupant acceptance of novel lighting schemes.

A more systematic application of this model of environment-behaviour relationships is Baron's positive affect model. He posits that environmental conditions influence emotional states which, in turn, influence cognitive processes and produce observable effects on task performance and social behaviours. Baron and Thomley (1994) reported that pleasant fragrances increased positive affect (feelings of happiness, interest), improved performance on an anagram task, and increased the participants' willingness to serve as uncompensated volunteers in future research. Baron, Rea, and Daniels (1992) reported three experiments on spectral power distribution and illuminance that

explored the same mechanism. Their results, although not conclusive, also support the existence of this mechanism; the lighting conditions that created positive affect tended to produce better performance on complex cognitive tasks and more favourable social behaviours (e.g., higher preference for collaboration to solve conflicts than for avoidance).

With the organising framework of this general model, we turn now to a model of lighting quality.

4.3.2. A Model of Lighting Quality

Discussions about quality are complicated by its intangible nature. One cannot measure quality in the same sense as one measures length, mass, or lumen output. Lighting quality is a hypothetical domain in the same sense as widely-known abstract concepts such as aggression, altruism, or political affiliation. In the language of a social scientist, such intangible entities are constructs. An important first step in understanding a construct is to establish measurement rules (Ghiselli, Campbell, & Zedeck, 1981). When we are satisfied that the appropriate rules have been established for a given construct, we say that we have determined that the construct is valid. The rules thus established are the operational definition of the construct.Cook and Campbell (1979), in their now-classic text on research design and analysis, advocate strongly that construct validity is most strongly established when hypotheses about constructs are successfully tested across multiple operations of the same definition of the construct. The definition thus operationalised must be based on a careful conceptual analysis of the construct. That is, one considers the nature of the intangible entity one wishes to measure from all angles, and creates several different sets of measurement rules that capture the important elements of it. Each set of measurement rules is one operation. The construct validity is established when one can demonstrate the same effect for the construct regardless of which operation is used to measure it.

Based on the environment-behaviour research tradition described above, the existing literature on lighting quality, and published accounts of designers' ideas about lighting quality (e.g., Wagner, 1975), we propose that lighting quality be defined as the degree to which the luminous environment supports the following requirements of the people who will use the space:

- visual performance;

- post-visual performance (task performance and behavioural effects other than vision);

- social interaction and communication;

- mood state (happiness, alertness, satisfaction, preference);

- health and safety;

- aesthetic judgements (assessments of the appearance of the space or the lighting).

This definition focuses on the relationships between the luminous environment, the uses to which the space will be put (tasks), and the people who will use the space. There is no fixed set of measurement operations by which lighting quality can be judged for a given lighting installation. Thus, for example, it is important to know that Baron et al. (1992) found similar results whether measuring social behaviour as the willingness to volunteer in future experiments or as the preferred method of conflict resolution.

Lighting quality, according to this definition, is not directly measurable, but is an emergent state created by the interplay of the lit environment and the person in that environment. Good lighting quality exists when a lighting system:

- creates good conditions for seeing;

- supports task performance or setting-appropriate behaviours;

- fosters desirable interaction and communication;

- contributes to situationally-appropriate mood;

- provides good conditions for health and avoids ill-effects;

- contributes to the aesthetic appreciation of the space.

The task for lighting researchers is to determine what luminous conditions (e.g., illuminance, luminance, uniformity, luminance distribution, spectral power distribution, flicker rate) provide good lighting quality. Clearly, the answer will not be universally applicable, for it will be influenced by settings, tasks, and individual differences. Moreover, lighting quality judgements will be influenced also by cultural and historical expectations. It is this complexity that leads some to pessimism about the likelihood of understanding lighting quality (e.g., Erhardt,

1994). It is true that the probability that one could develop a simple metric that will combine photometric values into a single-digit number, summarising all that the designer or engineer needs to know about lighting quality, is very low (cf. Boyce, 1995).

However, all is not lost. Behavioural science does possess the tools to allow us to understand which photometric conditions influence the human outcomes that interest us. We have the research design and statistical techniques to formulate predictive equations that will, within limits, allow us to distinguish between different lighting designs in terms of their effects on people. The challenge before us is to establish what luminous conditions lead to which behaviours, and for whom.

4.3.3.   Behavioural Science and Lighting Quality

Various research groups are already proceeding with a definition of lighting quality that incorporates a breadth of behavioural outcomes. For example, Boyce (1995a) included visual comfort and expectations as components of good lighting. The IESNA/International Association of Lighting Designers (IALD) Quality of the Visual Environment (QVE)/Metrics of Quality (MOQ) joint committee, (QVE is a successor to the former IESNA RQQ committee) currently uses a global rating of acceptability and ratings of visibility and comfort in its mini-experiments on aspects of lighting quality (Miller, McKay, & Boyce, 1995).In the 1980s, a team of researchers surveyed photometric conditions and conducted a survey of occupants' opinions of the lighting in 912 workstations in 13 buildings across the United States. The study was designed to examine the relationships between photometric measurements of the luminous environment and occupant ratings related to satisfaction. Understanding the relationship between the quality of the lit environment and the energy used to produce it was built in from the beginning (Marans, 1989). The research design followed a typical model for behavioural research, beginning with a conceptual model of the relationships to be examined and setting out specific, testable, hypotheses relating personal characteristics such as age and job level, physical environmental characteristics such as lighting and space, intermediate outcomes such as judgements of lighting quality and comfort, and final outcomes including well-being (e.g., job satisfaction, environmental satisfaction) and job-related health (e.g., headaches,

eye strain) (Marans, 1989). The measurement protocols were created to provide the data to test the hypotheses.

Five reports were generated from these data, of which two described data analyses: Marans and Brown (1987) reported descriptive statistics and simple bivariate correlations between photometric conditions and the behavioural data. Collins, Fisher, Gillette, and Marans (1989) reported more detailed analyses. Overall, it appeared that certain lighting systems were associated with dissatisfaction more than others. Indirect ambient systems with integrated furniture-mounted task lighting produced consistently lower ratings of satisfaction, brightness, and overall lighting quality that other systems. The pattern of luminances in the space appeared to be the reason for these low ratings. This cannot be interpreted as a permanent indictment of indirect ambient/furniture-mounted task lighting systems. It could be a function of the specific systems in use in the buildings surveyed; however, it calls attention to luminance distribution as an important element in good lighting design.

This field study resulted in a substantial database that can support further analyses. Marans and Yan (1989) examined the relationships between lighting quality, environmental satisfaction, and office enclosure. They found that lighting quality is an important determinant of environmental satisfaction; however, it is particularly important for workers in enclosed, private offices, and somewhat less important in open-plan offices.

Marans and Brown (1987) and Collins et al. (1989) distinguished between overall Ratings of Lighting Quality (RLQ) and Ratings of Visual Quality (RVQ). RLQ included a rating of satisfaction with lighting; ratings of the amount of light for the work and for reading; and, a rating of the degree to which lighting hindered the individual from doing his or her job well. RLQ tended to vary both in relation to the type of lighting and the type of primary task. RVQ was measured as the degree to which the occupant considered the workstation to be attractive, pleasant, interesting, spacious, and comfortable. RLQ and RVQ were highly correlated for most groups in the sample (on the order of .40), except for typists (Collins et al., 1989); that is, the nature of the work influenced the relationships between these two variables. The authors did not fully examine the relationships between RVQ and other variables, apparently satisfied with the knowledge that it relates to RLQ; however, some of the ratings included in the RVQ variable have been used as definitions of lighting quality by other researchers (e.g., Loe, Mansfield, &

Rowlands, 1994). The Collins et al. (1989) RLQ:RVQ correlation result is consistent with a multivariate definition of lighting quality that is task-specific, and deserves further examination.

4.3.4. Impediments to Understanding Lighting Quality

Despite the existence of a few behaviourally-based investigations, our understanding of lighting quality remains limited. Some writers hold that it is unlikely that lighting conditions have powerful effects on complex behaviours such as task performance, and that this accounts for the paucity of effects (e.g., Boyce, 1995a). Others have observed that lighting research has done poorly at respecting the scientific method (Gifford, 1994; Kaye, 1992; Tiller, 1990). The poor quality of most lighting-behaviour research is a powerful reason for our weak understanding of this domain.To establish the cause-and-effect relationships between lighting conditions and behaviour requires careful attention to research design so that:

plausible alternative explanations are eliminated (internal validity);

the intended constructs are both manipulated and measured (construct validity for both independent and dependent variables);

the statistical tests address the hypotheses in question (statistical conclusion validity); and,

the effects examined are general enough that they apply to situations other than the research setting (external validity).

That this validity terminology is unfamiliar to most readers reflects the rarity with which behavioural research methods are discussed by lighting researchers, even those who do research variously described as "psychological aspects", "subjective reactions", or "human factors". Standard texts appropriate to this discussion are those by Cook and Campbell (1979), Ghiselli, Campbell, and Zedeck (1981), and Kerlinger (1986), among others.

Previous reviews of lighting research have identified a variety of internal and external validity problems that unnecessarily restrict the conclusions that one may draw about lighting effects on people (e.g., Gifford, 1994; Gifford, Hine, & Veitch, in press; Veitch & McColl, 1994). Simply put, one reason for the lack of consensus about lighting quality is that much of the research is poorly performed and badly reported. Here, we focus only on the issue of construct validity: that is,

when we design and report lighting-behaviour research, how well do we specify the stimuli (lighting conditions) and the responses (covert and overt behaviours) that we wish to understand? Can we be certain that the effects we study are those we intend to study?

4.4.   Stimulus conditions.

Poor construct validity of independent variables is what researchers are describing when they say that an experiment is confounded (Cook & Campbell, 1979). In that case, more than one variable is included when stimulus conditions are changed. For example, Veitch and McColl (1994) noted that in studies of fluorescent lamp type, illuminance and lamp type were often confounded when lamps differing in luminous efficacy were replaced on a one-for-one basis. That is, full-spectrum fluorescent lamps, which produce approximately 70% as much light as cool-white lamps (Kaufman & Christensen, 1989), were installed in place of the same number of cool-white lamps (see, for example, Berry, 1983; Chance, 1983; Mayron, Ott, Nations, & Mayron, 1974), thereby lowering the illuminance at the same time as changing the spectral power distribution. Other symptoms of poor construct validity common to lighting research include inadequate specification of lighting conditions; photometric errors; and the use of an arbitrary selection of lighting conditions. The first two points are most familiar to the lighting community. The third reflects an absence of theory in lighting-behaviour research.Detailed photometric analysis is time-consuming; moreover, it is complicated by a lack of agreement about what measures constitute the minimum to characterise a scene. Not surprisingly, many research reports fail to include details that others consider essential. Tiller (1990) noted that the use of image acquisition systems to capture detailed photometric information could improve the state of lighting research considerably in increasing the speed of measurement, permitting a wide variety of point-to-point calculations and transformations, and in creating a permanent record of the scene. However, not all lighting researchers possess such systems because they are expensive, nor are currently-available systems suitable for most viewing situations (e.g., wide-angle views). The significant promise offered by these systems remains unfulfilled.

Lighting research and practitioners expend considerable effort and expense (even a modest illuminance meter costs on the order of $1000) to measure luminous conditions accurately. Nonetheless, the size of photometric errors in

field conditions is considerable (3-11% according to Ouellette [1993]). Luminance and illuminance meters are calibrated to incandescent standards under strict bench conditions and should be accurate with a similar source under similar conditions. However, field conditions are quite different. When one is making repeated measurements using an hand-held meter, one is unlikely to aim at precisely the same point on two occasions. Further errors creep in when one measures a source with spectral qualities that differ from the source to which the meter was calibrated. These random and systematic errors in specifying the stimulus conditions decrease the probability of detecting lighting-behaviour relationships. It is axiomatic that greater care should be taken with such measurements; guidelines are provided by Ouellette (1993). Significant errors in measuring stimulus conditions constitute a threat to the construct validity of the independent variable in the lighting-behaviour relationship. If we don't know what the stimulus is, then even if a behavioural effect is observed, it will have no meaning.

Even accurately-measured stimulus conditions can fail to have construct validity. The problem is that for any given setting, there is an almost infinite number of possible lighting choices. This is a boon to designers, but poses a problem for researchers: Which lighting installations should be the focus of investigation? Past research, with the exception of the literature on visual performance, has been atheoretical. Each researcher has selected a range of lighting conditions without presenting a detailed reasoning for the choice. For example, Katzev (1992) compared preferences and task performance in four enclosed offices with four lighting systems. One was deliberately chosen as non energy-efficient; the other three systems were energy-efficient. There are, however, many other possible choices for energy-efficient office lighting than were (or could have been) examined in this experiment. Without a theoretical reason for the choice of lighting systems, it is impossible to build a systematic understanding. Each study becomes an examination of the lighting hardware currently employed, and each study can be superseded by the next wrinkle in luminaire or lamp development. A theoretical basis for the selection of lighting conditions for behavioural research would provide a body of knowledge that can be handed down to future generations (cf. Kaye, 1992; Tiller, 1990).

4.4.1. Behavioural outcomes.

If lighting quality consists in the fit between human activity and luminous conditions in a given setting, then it follows that to assess lighting quality requires accurate measurement of the relevant human activities, as well as accurately specified, appropriate lighting conditions. Lighting research has typically failed to attend to the response side of the equation, possibly because many researchers approach lighting from a background on the technical (stimulus) side.Cook and Campbell (1979) recommended that for any construct there should be multiple measures, preferably using different response modalities. In this manner, one can overcome the inevitable biases and error inherent in any one behavioural measure. The strength of one's conclusion is stronger if one can obtain the same pattern of outcomes with each measure. Thus, for example, if one studies prejudice, one might obtain responses from a group of people using a standardised survey of racial attitudes and also observe their behavioural responses during a conversation with a member of a visible minority. In the case of lighting quality, the need for multiple measures is all the more important because every lighting installation serves multiple purposes: to satisfy requirements for visibility, task performance, social interaction, mood, safety and health, and aesthetics. The construct itself is multi-dimensional. Comparatively few investigations have explicitly addressed lighting-behaviour relationships in this way; exceptions that have done so include Boyce and Rea (1994) and Kuller and Wetterburg (1993).

In the behavioural sciences, almost every measurement is an attempt to define rules that capture a construct. In research journals, therefore, it is necessary to be specific about what behaviour was measured and to provide information about the data. At a minimum this requires, for every variable, a statement of the operations used to make the measurement and a report of the overall mean, standard deviation and reliability of the measurement, as well as the means and standard deviations for the experimental groups. Without this information, the reader cannot assess the adequacy of the measurement and, therefore, has no basis on which to judge whether or not the data relate to the intended construct. The statistical reporting is also important because it permits re-analysis of the data by other researchers (e.g., by using meta-analytic techniques to combine data from many similar studies [Gifford et al., in press]).

Reliability can be assessed in many ways, the choice of which depends on the nature of the construct and the manner of measurement (Ghiselli, Campbell, & Zedeck, 1981). For scales composed of several items, the most commonly-reported statistic is the internal consistency reliability, or Cronbach's alpha. Cronbach's alpha is an average of the correlation between all possible pairs of items, and reflects the extent to which the items agree. If all of the items in a scale measure the same construct, agreement should be high.

One of the more frequent occurrences in the lighting quality literature is the use of multivariate techniques such as multidimensional scaling (e.g., Flynn, Spencer, Martyniuk, & Hendrick, 1973) and factor analysis (e.g., Loe, Mansfield, & Rowlands, 1994). These are powerful tools for all behavioural science, but they are consistently misused by lighting researchers. The interpretation of the results of such analyses is an art as much as a science, for there are no firm decision rules concerning these techniques, as there are for statistical tests based on probability functions (e.g., analysis of variance). Given this flexibility, it is critical that the researcher establish the robustness of the outcomes being interpreted. A robust outcome for these multivariate techniques demands a minimum ratio of ten participants for every item (Kerlinger, 1986). That is, if there are 18 bipolar rating scales in a factor analysis, there must be at least 180 participants rating them. Almost no lighting research reaches this level of robustness (e.g., Loe et al., 1994; Flynn et al., 1979; Kuller & Wetterburg, 1993). This means that it is quite likely that the results now taken for granted are biased, and may reflect influences other than the interpretation proffered by the researchers.

4.5.   Prospects for Lighting Quality

The failure to reach agreement about lighting quality has been seriously impeded by the failure to recognise the question as one part of the larger attempt to determine the nature of environmental quality, provided to support human activity. The outcomes that benefit from good lighting quality are behavioural outcomes. Behavioural scientists have been remiss in not looking to the lighting literature for a different perspective on this issue. Lighting researchers have been remiss in not following the behavioural literature, and in particular its standards for research design, methods, statistical analysis, and reporting.   In consequence, we know less about lighting quality than we should after more than a century of lighting practice and ninety years of its professional organisations.However, there are encouraging hints to be followed. The

IESNA/IALD QVE/MOQ committee has proposed a new concept of "volumetric brightness" as a means to describe luminance distribution effects on acceptability (Miller et al., 1995) and is continuing its work (e.g., Veitch, Miller, McKay, & Jones, 1996). Experimental work on these concepts also in research now under way at the National Research Council of Canada, Institute for Research in Construction (described in Veitch & Newsham, 1995), and, no doubt, by other groups.

These efforts can answer empirical questions about how luminous conditions affect important outcomes for individuals. It cannot provide the moral judgement about how to weight the outcomes when what is best for the individual appears to be costly for the organisation. In an ideal world, there would be no trade-off between job performance and employee well-being. However, we are a long way from establishing with any scientific certainty the existence of indirect effects such as the effect of good working conditions on the organisational bottom line (e.g., by improving mood and reducing absenteeism), despite many anecdotal reports claiming that such effects exist. Long-term, multidisciplinary studies of the effects of physical and organisational conditions on both individual and organisational outcomes appear not to exist, judging by an extensive literature search. Until such knowledge exists, the imperative to provide good working conditions, beyond the merely tolerable or acceptable, will remain a complex decision weighing the cost of responding to complaints, the cost of providing the space, and the moral responsibility of employer to employee.

5. Indoor work places lighting recommendation.

5.1. EN 12464-1

This section is designed to facilitate the application of EN 12464-1 "Lighting of work places – Indoor work places" for lighting system planning and design. The European standard EN 12464-1 is the result of detailed discussion over several national standards that were produced with the aim of creating a unique general normalization frame. What has changed from most of the previous national standards are a number of basic concepts and methods of assessing individual quality features. Particularly significant changes are:

- introduction of the task area and the immediate surrounding area

- introduction of maintained illuminance

- introduction of a new method of rating direct glare (UGR)

- Introduction of new reflected glare rating limits for workstations with display screen equipment (DSE).

EN 12464-1 lists the lighting criteria still required for lighting quality:

- agreeable luminous environment

- harmonious luminance distribution

- adequate illuminance for the activities listed in the "Schedule of lighting requirements"

- good uniformity

- limitation of direct and reflected glare and veiling reflections

- correct directional lighting and agreeable modeling

- suitable color appearance and color rendering

- avoidance of lamp flicker and stroboscopic effects

- account of daylight

5.1.1. Maintained illuminance E_m

Illuminance levels impact significantly on the speed, ease and reliability with which visual tasks can be performed. The illuminance values specified in the standard for the task area and the immediate surrounding area are maintained illuminance values, i.e. values which the average illuminance on a reference surface must not fall below. In other words, they are the average illuminance values reached when maintenance needs to be carried out.

5.1.2. Task area and immediate surrounding area

The task area is defined as the partial area in the work place in which the visual task is carried out. The visual performance required for the visual task is determined by the visually relevant elements (size of objects, background contrast, luminance of objects and presentation time) of the activity performed.

For places where the size and/or location of the task area are unknown, the area where the task may occur should be taken as the task area. The immediate surrounding area is defined as the area surrounding the task area within the field of vision. According to EN 12464-1, this surrounding area should be at least 0.5 m wide and can thus be seen as a band around the task area.

When a lighting system is designed, the precise location of the visual task often cannot be defined because

- the precise location of the task area is unknown

- the activity performed involves a number of different visual tasks.

In such cases, it is recommended that several task areas should be combined to form a larger area (referred to below as the working area). Where the location of work places is unknown, this working area can also be the entire room. If illuminance distribution in these larger areas has a uniformity of g_1 _ 0.6, it can be assumed that the required $g_1 \geq 0,7$ is always fulfilled in the individual task areas (see Figure 5-1 for example).

Task areas can be defined as following:

- Areas where different visual tasks may be performed are normally on the work surface, in movement space and on surfaces used for tasks directly related to the activity.

- When defining task areas, attention also needs to be paid to vertical surfaces such as boards and other inclined surfaces as well as to horizontal surfaces in the room and in the working area.

- Where the immediate surrounding area is the marginal strip, it should not be rated separately because, as a general rule, the requirements the surrounding area needs to meet are fulfilled automatically. Care must be taken here to ensure there are no task areas in the marginal strip.
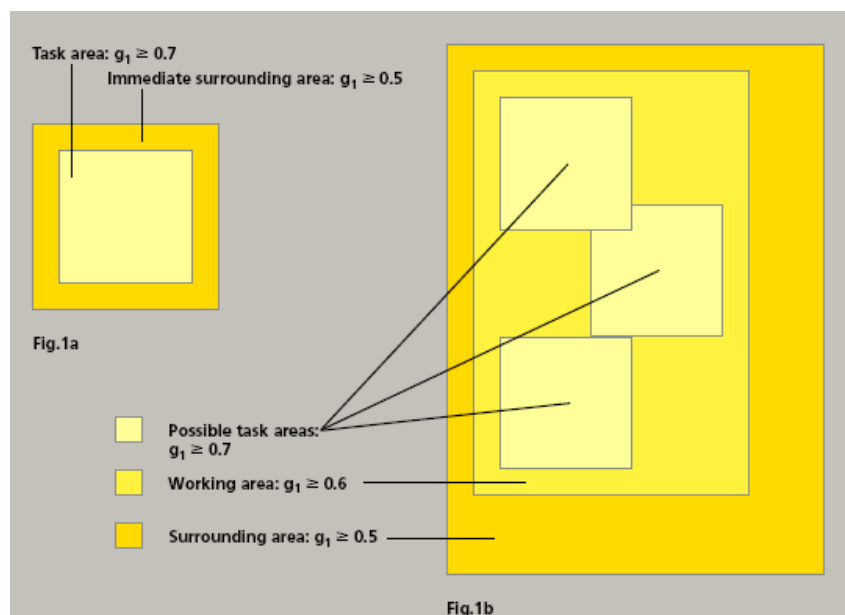
Figure 5-1 Task area and immediate surrounding area according EN 12464.
Working area where task may be located, and surrounding area.

5.1.2.1 *Examples of how task areas can be defined for lighting design*

Office with single workplace

The location of the workplace is known. Working areas encompass the desktop and user space. The height of the working area is assumed to be 0.75 m. The surrounding area is taken to be the rest of the room less a 0.5 m wide marginal strip.

Figure 5-2 DSE working area (yellow) encompasses work surface (grey desktop) and user space (red)
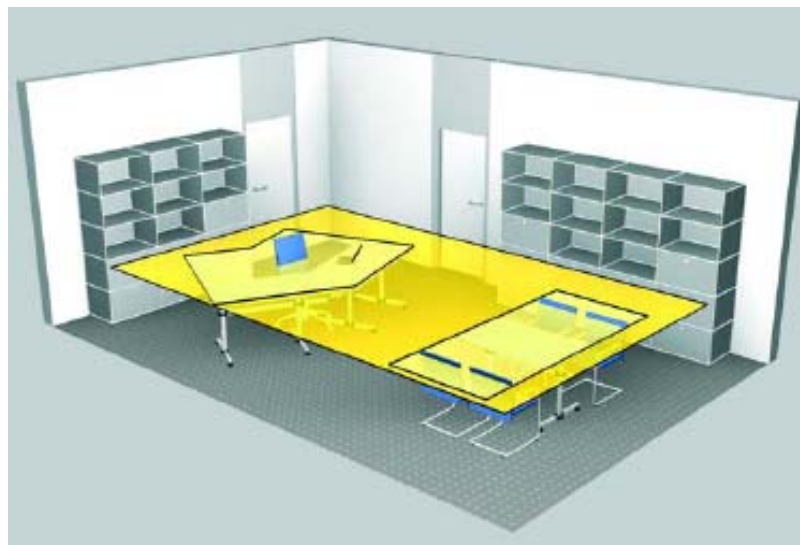
Figure 5-3 Horizontal working areas in an office: DSE work" (light yellow, left) and "conference" (light yellow, right) with "surrounding area" (dark yellow). Reference height for illuminance: 0.75 m above floor level.

Office with unknown arrangement of workplaces

If the arrangement of workplaces is completely unknown, the working area should be taken as the whole room less a marginal strip. Where planning documents show workplaces close to windows, a correspondingly wide strip can be taken as the working area. Planned uniformity can be $g_1 \geq 0.6$. Experience shows this is

enough to ensure that a minimum of 0.7 uniformity is observed at the individual workplaces. The surrounding area is the rest of the room.
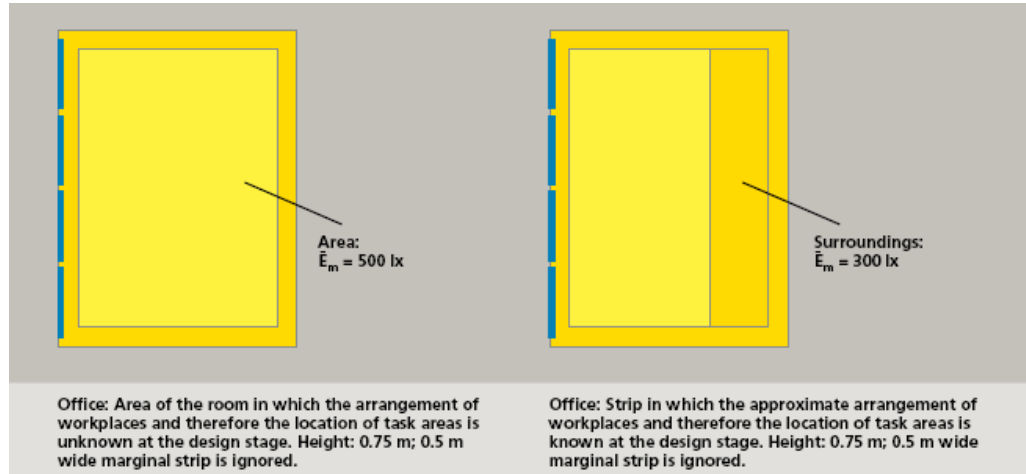
Figure 5-4 Working areas where the precise location of workplaces is unknown.

Training or teaching rooms with flexible arrangement of desks

The desks are often rearranged in classrooms, so the working area should be taken as the whole room less a 0.5 m wide marginal strip. Planned uniformity can be $g_1 \geq 0.6$. Experience shows this is enough to ensure that a minimum of 0.7 uniformity is observed at the individual desks.

Office-like room with possible arrangement of workplaces extending to the boundaries of the room.

Where it is known that working areas may extend to the boundaries of the room but the precise location of the working areas is unknown, the whole room is taken as the working area without deducting any marginal zones. Planned uniformity can be $g_1 = 0.6$. Experience shows this is enough to ensure that a minimum of 0.7 uniformity is observed at the individual workplaces.

Shelving systems and other vertical surfaces

Shelving systems and cabinets can be vertical task areas (e.g. ticket counter, accounts section). The vertical area starts 0.5 m above floor level and ends at the height of the task area; in the case of an office shelving system, this is 2 m above floor level.
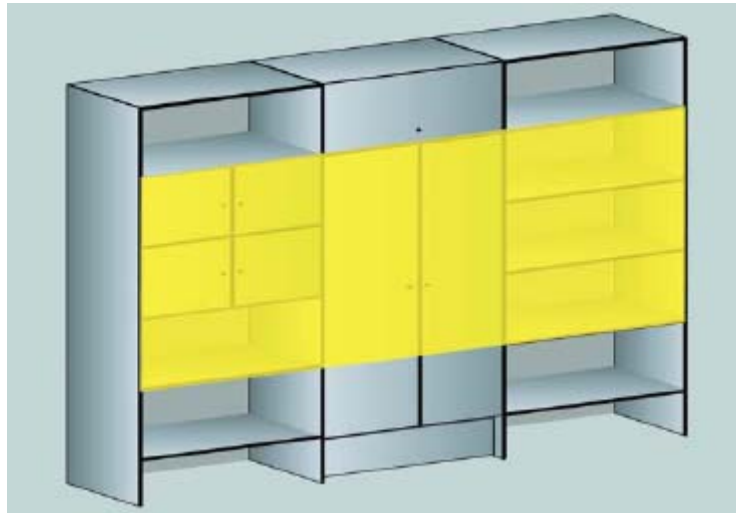
Figure 5-5 Position of the vertical task area.

Corridor

For corridors up to 2.5 m wide, it is recommended that the individual task areas should be taken as central 1 m wide strips on the floor and combined to form a single large task area. The rest of the space should be regarded as the surrounding area. In wider corridors, the central strip task area should be adjusted accordingly. Where applicable, a lateral strip (up to 0.5 m wide) should be deducted along each wall, provided it is not part of the traffic zone. Vertical task areas such as doors, door handles and signs must also be borne in mind, although no particular illuminance values are specified.
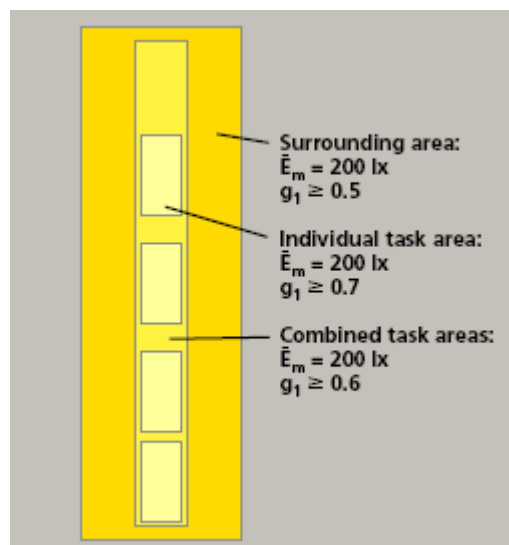
Figure 5-6 Corridor example

In corridors the individual task areas are small. For lighting design purposes, they can be combined to form a single large area. Attention must be paid to the different uniformities. 200 lux illuminance is required (during the day) for corridors in health care establishments.

Hall with zones for different activities

Halls generally incorporate a number of task areas with diverse illuminance requirements. Where this is the case, it is recommended that, as a first step, a general hall lighting concept should be developed treating the whole hall – less a 0.5 m wide marginal strip along the walls – as a task area with the lowest requirements. The immediate surrounding area (marginal strip) does not require separate assessment because, as a general rule, the requirements which the surrounding area needs to meet are fulfilled automatically. For other task areas with different requirements, appropriate, preferably rectangular task areas with their own surrounding areas should be defined and provided with the illuminances and uniformities required.

5.1.3. Glare limitation

Glare is the sensation produced by excessively bright areas or excessively marked differences in luminance within an observer's field of view. Glare which causes direct impairment of vision is known as disability glare. Glare which is found disturbing, which impairs our sense of wellbeing, is known as discomfort glare.

5.1.3.1 Uniformity

Task area should be illuminated as uniformly as possible. The uniformity of the task area and the immediate surrounding areas shall be not less than values given in the following table.

Task illuminance lx	Illuminance of immediate surrounding areas lx
≥750	500
500	30
300	200
≤200	E_{task}
Uniformity: ≥0,7	Uniformity ≥ 0,

Figure 5-7 uniformities and relationship of illuminances of immediate surrounding areas to task area.

5.1.3.2 Rating discomfort glare by the UGR method

The degree of discomfort glare caused by a lighting system can be determined by the UGR method. Depending on the difficulty of the visual task, the UGR_L limit should not be exceeded. In Figure 5-8 are shown examples of maximum limits:

Examples of maximum UGR_L limits

Technical drawing	≤ 16
Reading, writing, classrooms, computer work, inspections	≤ 19
Work in industry and craft workshops, reception	≤ 22
Rough work, staircases	≤ 25
Corridors	≤ 28

Figure 5-8 Example of maximum UGR_L limits

A lighting system should be appropriate for the relevant UGL category (e.g. "≤19"). UGR values can be ascertained by the tabular method. UGR tables are available from manufacturers and incorporated in commercial lighting calculation software. For initial luminaire selection, it is advisable to use the tabular value of

the reference room (4H / 8H) based on a spacing-to-height ratio of 0.25). Individual UGR values in a lighting system can be calculated using CAD software. This may be useful for designing systems where glare is a critical factor but it does not indicate the standard of glare limitation of the installation as a whole.

5.1.3.3   _Shielding_

As excessively bright light sources in the field of view can cause glare, lamps must also be suitably shielded. For luminaires which are open from below or fitted with a clear enclosure, the shielding angle is defined as the angle between the horizontal and the line of sight below which the luminous parts of the lamp in the luminaire are visible.
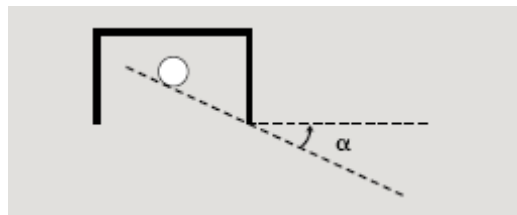
Figure 5-9 Shielding angle α

The following table shows minimum shielding angles at specific lamp luminances.

Lamp luminance in cd/m²	Minimum shielding angle
20,000 to < 50,000 e.g. fluorescent lamps (high output) and compact fluorescent lamps	15°
50,000 to < 500,000 e.g. high-pressure discharge lamps and incandescent lamps with matt and inside-coated bulbs	20°
≥ 500,000 e.g. high-pressure discharge lamps and incandescent lamps with clear bulbs	30°

Figure 5-10 Minimum shielding angles specified by DIN EN 12464-1

The minimum shielding angles for the lamp luminances shown need to be observed for all emission planes. They do not apply to luminaires with only a top-side light exit opening or to luminaires mounted below eye level.

5.1.3.4   *Luminance limits for avoiding reflected glare*

As well as rating direct glare due to excessively luminant surfaces, special attention needs to be paid to avoiding reflected glare, which is the glare caused by light reflecting from shiny surfaces. Reflections of excessively bright luminous parts of a luminaire can seriously interfere with work at a screen or even at a keyboard. So care needs to be taken to arrange suitable luminaires so that no disturbing reflections are created. In EN 12464-1, luminance limits are specified for luminaires which could reflect along normal lines of sight from a screen inclined at up to 15°. As a general rule, 1,000 cd/m2 needs to be observed for positive display LCD or CRT monitors with a good anti-reflective or anti-glare finish and 200 cd/m2 for negative display CRT monitors such as those used at CAD workstations. The luminances specified must not be exceeded at elevation angles ≥65° from the downward vertical in any radiation plane.
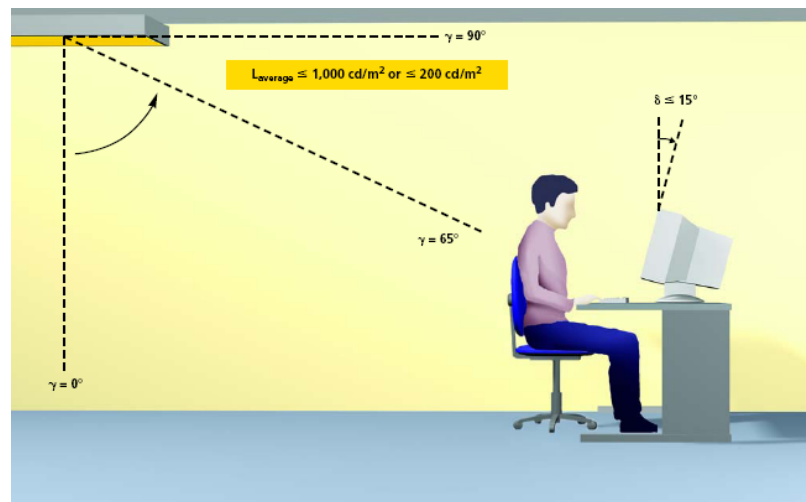
Figure 5-11 Critical zone of radiation (γ≥65°) for luminance could give rise to reflected glare on a screen.

5.1.3.5 *Indoor lighting system glare rating*

Direct glare caused by luminaires in an indoor lighting system can be rated using the CIE Unified Glare Rating (UGR) method. This method is based on the formula:

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

where:

- L_b = the background luminance in cd/m^2, calculated as E_{ind} / π, in which E_{ind} is the vertical indirect illuminance at the observer's eye,

- L = the average luminance in cd/m^2 of the luminous parts of the luminaire in the direction of the observer,

- ω = the solid angle in sr of the luminous parts of the luminaire visible from the vantage of the observer,

- p = the position index for each individual luminaire.

Use of the UGR method is restricted to direct luminaires and direct /indirect luminaires with an indirect component up to 65 percent. In the case of luminaires with an indirect component >65 percent, the UGR method produces unduly favorable ratings. Generally speaking, however, glare can be largely ruled out in the case of these luminaires because of the very low glare potential of the direct component. According to CIE Publication 117, the UGR method can no longer be used for large light sources (solid angle > 1 sr) or small light sources (solid angle <0.0003 sr). Large light sources can be individual luminaires with luminous surfaces > 1.5 m^2, luminous ceilings with at least 15 percent luminous panelling or uniformly illuminated ceilings. As the dazzling effect of large light sources depends to only a small extent on their position index, solid angle or background luminance, the glare caused by large light sources can be fairly approximated on the basis of luminance and limited by defining a maximum permissible value. In DIN 5035 Part 1, the maximum permissible luminance was set at 500 cd/m^2. In LiTG Publication 20 on the UGR method, the limit recommended for limiting glare to a UGR of 19 is 350 cd/m^2 for large rooms and 750 cd/m2 for small rooms. Small light sources visible below a solid angle<0.0003 sr are generally found in the following situations:

- in low interiors (room height h < 3 m e.g. office lighting systems). Downlights, for example, can occupy small solid angles here if they are a fairly long way from the observer.

- in high halls (e.g. sports and industrial hall lighting systems). High-bay reflector luminaires, for example, are visible to the observer at small solid angles here because of their high mounting height.

In both cases, glare due to light sources < 0.0003 sr cannot be ruled out. Drawing on field study findings, LiTG Publication 20 therefore recommends that the lower solid angle limit should be abolished to avoid situations where glare fails to be anticipated because disturbing luminaires are below the solid angle limit and are therefore disregarded.

5.1.3.6   *Rating by the tabular method*

According to the standard, the degree of direct glare caused by a lighting system can be determined using the UGR tabular method. Here, the system concerned is compared with a standard table listing UGR values for 19 standard rooms and various reflectance combinations for the selected luminaire. The computations for the 19 standard rooms are based on the assumption that the observers – positioned at the midpoint of each wall – observe the luminaires along and across their lines of sight along the room axes. The luminaires are mounted in a regular grid on the luminaire plane, the midpoints of the luminaires set at a distance 0.25 times the distance H between the luminaire plane and the height of the observer's eye and the midpoints of the luminaires closest to the walls set half as far from the wall as the luminaire midpoints from each other. When selecting suitable luminaires, care must be taken to ensure that only tables with the same spacing-to-height ratio and the same lamp luminous flux are compared. A "table of corrected standardized glare ratings" is shown overleaf.

5.1.3.7   *Rating in the reference room*

If not all UGR tables are available or if dimensions or reflectances are unknown at the design stage, glare can be rated using the UGR value for the reference room. The reference room is a medium-sized room measuring 4H / 8H with ceiling, wall and floor reflectances of 0.7, 0.5 and 0.2 respectively. The ranking resulting from comparison of different lighting systems is generally maintained provided the UGR values compared were computed for the same luminaire

midpoint spacing and the same lamp luminous flux. At all events, glare rating must be based on the installation values of the lighting systems and the rated values of the lamps used. Whichever method is used, the UGR values thus established must not exceed the UGR limits for interiors, tasks and activities stated in the "Schedule of lighting requirements" tables contained in the standard.

5.1.4. Lighting system maintenance

With increasing length of service, the luminous flux delivered by a lighting system decreases as lamps and luminaires age and accumulate dirt. The anticipated decline of luminous flux depends on the choice of lamps, luminaires and operating gear as well as on the operating and environmental conditions to which they are exposed. To ensure that a specific lighting level – expressed by maintained illuminance – is reached for a reasonable period of time, an appropriate maintenance factor needs to be applied by the lighting designer to take account of this decrease in system luminous flux. The maintenance factor is the ratio of maintained illuminance to the level of illuminance when the lighting system is new.
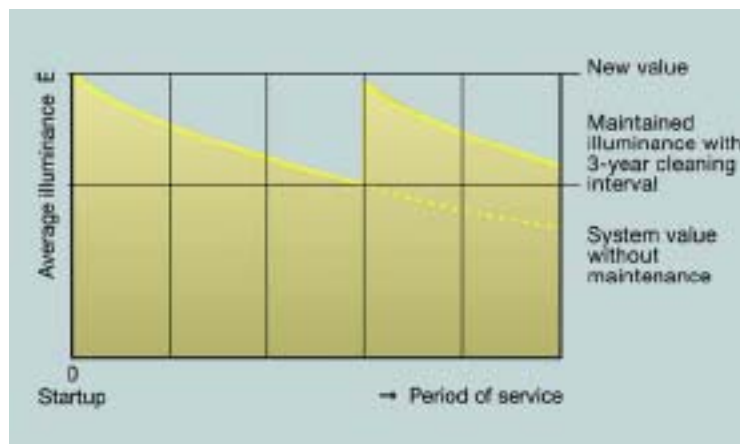
Figure 5-12 Illumnance during the period of service of a lighting system.

5.1.4.1   *Maintenance factor documentation.*

The designer needs to prepare a maintenance schedule for the lighting system. In particular, this should specify the frequency of lamp replacement, luminaire

and room cleaning intervals and, where appropriate, the cleaning techniques used. The maintenance factor shown in the example (Figure 5-13) is 0.73 under the following conditions:

- lamps are replaced in groups every 12,000 operating hours

- luminaires are cleaned every year

- room surfaces are cleaned every two years.

Project:		
Room:		
Processed by:		
Date:	02.03.2006 / 11:47:00	
Luminaire		
Description:	luminaire xyz	
Article number:	42157193	
Luminaire type:	enclosed IP2X	
Cleaning interval in years:	1.0	
Luminaire maintenance factor LMF:		0.88
Lamp		
Description:	T16 High Ouput	
Watt rating:	54 W	
Lamp replacement:	group	
Operating gear:	EB	
Lamp maintenance in years:	2.0	
Operating hours per lamp/year:	6,000	
Lamp lumen maintenance factor LLMF:		0.91
Lamp survival factor LSF:		0.98
Room		
Length:	8 m	
Depth:	8 m	
Height:	3 m	
Environment	clean	
Room cleaning interval in years:	2.0	
Type of lighting:	direct	
Room maintenance factor RMF:		0.96
Maintenance factor		0.73

Figure 5-13 Example of maintenance factor documentation

Determination of maintenance factor The maintenance factor (MF) is a multiple of factors and is determined as follows:

MF = LLMF x LSF x LMF x RMF

where:

LLMF takes account of the decline in lumen output LSF takes account of the effects of lamp ageing, LMF takes account of the reduction of light output due to dirt accumulating on luminaires RMF takes account of the reduction in reflectance

due to dirt deposition on room surfaces. In many cases, it can be assumed that "lamp failure maintenance factor = 1" because the failure of individual lamps leads to unacceptable falls in lighting Indoor work places level, which is why individual lamp replacement is required. Individual maintenance factor values can be obtained from manufacturers or found in standard average value curves and lighting publications such as CIE 97. Examples of maintenance factors and their inverse counterparts, new-value factors, are cited below on the basis of data available at present. Lamps are replaced individually as soon as they fail and are group replaced when illuminance falls to the maintained illuminance level.

Maintenance factor	New-value factor	Example
0.80	1.25	very clean environment, maintenance cycle 1 year (luminaire cleaning), 2,000 burning hrs/year with lamp replacement every 8,000 hrs, individual replacement, direct and direct/indirect luminaires with little tendency to collect dust, LLMF = 0.93; LSF = 1.00; LWF = 0.90; RMF = 0.96
0.67	1.50	normal environmental pollution load, maintenance cycle 3 years, 2,000 burning hrs/year with lamp replacement every 12,000 hrs, individual replacement, direct and direct/indirect luminaires with little tendency to collect dust, LLMF = 0.91; LSF = 1.00; LWF = 0.80; RMF = 0.90
0.57	1.75	normal environmental pollution load, maintenance cycle 3 years, 2,000 burning hrs/year with lamp replacement every 12,000 hrs, individual replacement, luminaires with normal tendency to collect dust, LLMF = 0.91; LSF = 1.00; LWF = 0.74; RMF = 0.83
0.50	2.00	dirty environment, maintenance cycle 3 years, 8,000 burning hrs/year with lamp replacement every 8,000 hrs, LLB, group replacement, luminaires with normal tendency to collect dust, LLMF = 0.93; LSF = 0.93; LWF = 0.65; RMF = 0.94

Figure 5-14 Examples of maintenance factors for interior lighting systems with fluorescent

lamps

Maintenance factor	New-value factor	Example
0.80	1.25	very clean environment, maintenance cycle 1 year, 2,000 burning hrs/year with lamp replacement every 2,000 hrs, individual replacement, direct and direct/ indirect luminaires with little tendency to collect dust, LLMF = 0.87; LSF = 1.00; LWF = 0.94; RMF = 0.97
0.67	1.50	clean environment, maintenance cycle 2 years, 2,000 burning hrs/year with lamp replacement every 4,000 hrs, individual replacement, direct and direct/ indirect luminaires with little tendency to collect dust, LLMF = 0.81; LSF = 1.00; LWF = 0.90; RMF = 0.96
0.57	1.75	normal environment pollution load, maintenance cycle 2 years, 2,000 burning hrs/year with lamp re-placement every 4,000 hrs, individual replacement, direct/indirect luminaires with little tendency to collect dust, LLMF = 0.81; LSF = 1.00; LWF = 0.82; RMF = 0.83
0.50	2.00	normal environmental pollution load, maintenance cycle 2 years, 2,000 burning hrs/year with lamp replace-ment every 4,000 hrs, individual replacement, luminaires with normal tendency to collect dust, LLMF = 0.81; LSF = 1.00; LWF = 0.74; RMF = 0.83

Figure 5-15 Examples of maintenance factors for interior lighting systems with metal halide lamps.

5.1.4.2 _Reference maintenance factors_

The multiplication described above to determine the maintenance factor from the individual components offers the lighting designer many opportunities to optimise lighting system maintenance intervals – and therefore lighting system investment and operating costs – through the use of suitable lamps, luminaires and operating gear. For rough project planning or where detailed information is not available, it seems reasonable initially to assume a reference maintenance factor of 0.67. Later, when the lamps and luminaires to be used have been identified and the environmental and operating conditions are known, the reference value can be modified.

Where one or more of the following – potentially inter-impacting – conditions applies, maintenance factors can generally be increased.

- Use of lamps subject to little light depreciation (depending on burning life), e.g. fluorescent lamps
- Use of luminaires with little tendency to collect dust
- Use of operating gear which lengthens lamp life (e.g. EB)
- Short periods of service per year
- Low number of operations per year
- Short cleaning and/or maintenance intervals, individual and group lamp replacement
- Low exposure to dust in the atmosphere
- Low tendency to collect dust and/or for reflecting surfaces to become discoloured

0.8

Reference value: 0.67

- Use of lamps subject to marked light depreciation (depending on burning life), e.g. metal halide lamps
- Use of luminaires with tendency to collect dust
- Long periods of service per year
- Large number of operations per year
- Long cleaning and/or maintenance intervals (e.g. because of difficult access), only group lamp replacement
- High exposure to dust or exposure to tobacco smoke
- Tendency to collect dust and/or for reflecting surfaces to become discoloured

0.5

Where one or more of the above – potentially inter-impacting – conditions applies, maintenance factors generally need to be reduced.

Figure 5-16 MF value deviation according to different conditions

5.1.5.   Calculation grid

In addition to the content of EN 12464-1, the requirements set out for calculation grids in EN 12193 "Sports Lighting" are also adopted and recommended. In principle, the grid required to determine average illuminances and uniformities depends on the size and shape of the reference surface (task area, working area or surrounding area), the geometry of the lighting system, the luminous intensity distribution of the luminaires used, the required accuracy and the photometric quantities to be evaluated.

	Longest dimension of zone or room	Grid size
Task area	approx. 1 m	0.2 m
Small rooms/room zones	approx. 5 m	0.6 m
Medium-size rooms	approx. 10 m	1 m
Large rooms	approx. 50 m	3 m

Figure 5-17 Recommended grid size for room and room zones

Experience has shown that the following grid size p should not be exceeded:

$$p = 0.2 x 5^{\log_{10} d}$$

where:

p is the grid size and d the relevant dimension of the reference surface. The number of points is then given by the next whole number of the ratio d to p. Rectangular reference surfaces are subdivided into smaller, roughly square rectangles with the calculation points at their centre. The arithmetic mean of all the calculation points is the average illuminance. Where the reference surface has a length to width ratio between 0.5 and 2, the grid size p and therefore the number of points can be determined on the basis of the longer dimension d of the reference area. In all other cases, the shorter dimension needs to be taken as the basis for establishing the spacing between grid points. For non-rectangular reference surfaces, i.e. surfaces restricted by irregular polygons, grid size can be determined analogously using an appropriately dimensioned circumscribing rectangle. Arithmetic means and uniformities are then established taking only the calculation points within the restricting polygons of the reference surface. For ribbon-like reference surfaces, which normally result from the surrounding areas evaluated, the dimension of the ribbon at its widest point should be taken as the basis for determining grid size. However, the grid size thus established must be no greater than half the dimension of the ribbon at its narrowest point if that is 0.5 m or more. Arithmetic means and uniformities are again determined taking only the calculation points within the ribbon.
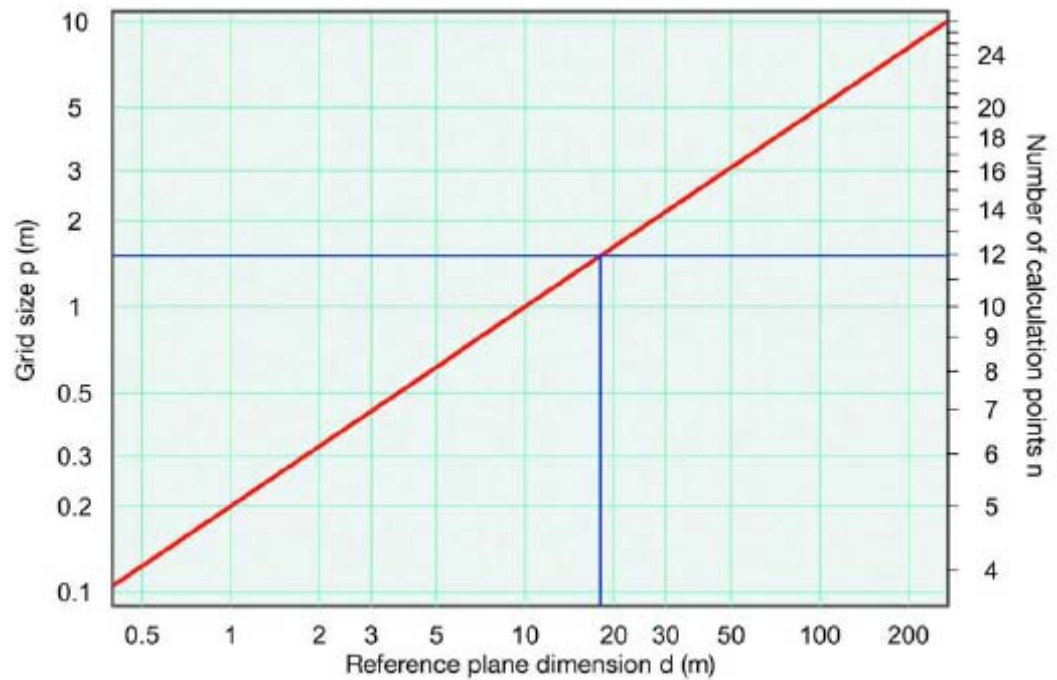
Figure 5-18 Grid size as a function of reference plane dimensions

5.2. PrEN 15193

5.2.1. Preface

This European standard was devised to establish conventions and procedures for the estimation of energy requirements of lighting in buildings, and to give a methodology for a numeric indicator ofenergy performance of buildings. It also provides guidance on the establishment of notional limits for lighting energy derived from reference schemes. Having the correct lighting standard in buildings is of paramount importance and the convention and procedures assume that the designed and installed lighting scheme conforms to good lighting practices. For new installations the design will be to EN 12464-1, Light and Lighting – Lighting of workplaces – Part 1: Indoor work places. The standard also gives advice on techniques for separate metering of the energy used for lighting that will give regular feedback on the effectiveness of the lighting controls. The methodology of energy estimation not only provides values for the numeric indicator but will also provide input for the heating and cooling load impacts on the combined total energy performance of building indicator. The methodology and format of the

presentation results would satisfy the requirements of the EC Directive on Energy Performance of Buildings 2002/91/EC.

5.2.2. Scope

This standard specifies the calculation methodology for the evaluation of the amount of energy used for indoor lighting inside the building and provides a numeric indicator for lighting energy requirements used for certification purposes. This standard can be used for existing buildings and for the design of new or renovated buildings. It also provides reference schemes to base the targets for energy allocated for lighting usage. This standard also provides a methodology for the calculation of instantaneous lighting energy use for the estimation of the total energy performance of the building. Parasitic powers not included in the luminaire are excluded. In this standard, the buildings are classified in the following categories: Offices, Education buildings, Hospitals, Hotels, Restaurants, Sports facilities, Wholesale and retail services and Manufacturing factories. In some locations outside lighting may be fed with power from the building. This lighting may be used for illumination of the facade, open-air car park lighting, security lighting, garden lighting, etc. These lighting systems may consume significant energy and if they are fed from the building, this load will not be included in the Lighting Energy Numeric Indicator or into the values used for heating and cooling load estimate. If metering of the lighting load is employed, these loads may be included in the measured lighting energy.
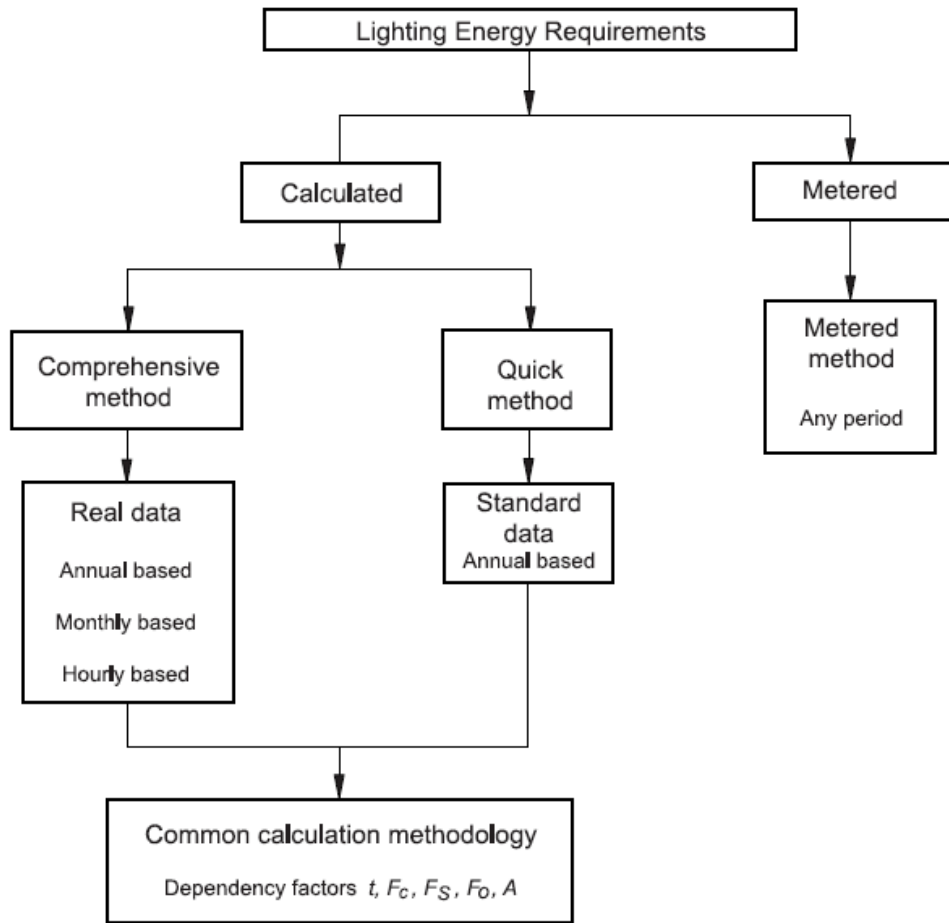
Figure 5-19 Flow chart illustrating alternative routes to determine energy use

5.2.3.   **Calculating energy used for lighting**

5.2.3.1   Total energy used for lighting

The total estimated energy required for a period in a room or zone shall be estimated by the equation:

$$W_t = W_{L,t} + W_{P,t} \qquad [kWh] \qquad\qquad 5\text{-}1$$

W_t: total energy used for lighting is the energy consumed in period t, by the luminaires when operating, and parasitic loads when the luminaires are not operating, in a room or zone, measured in kWh

$W_{L,t}$: energy consumption used for illumination is the energy consumed in period t, by the luminaires to fulfil the illumination function and purpose in the building, measured in kWh

W$_{P,t}$: luminaire parasitic energy consumption is the parasitic energy consumed in period t, by the charging circuit of emergency lighting and by the standby control system controlling the luminaires, measured in kWh.

An estimate of the lighting energy required to fulfil the illumination function and purpose in the building (W$_{L,t}$) shall be established using the following equation:

$$W_{L,t} = \sum \left\{ \left(P_n \times F_C \right) \times \left[\left(t_D \times F_o \times F_D \right) + \left(t_N \times F_D \right) \right] \right\} / 1000 \qquad [kWh] \qquad 5\text{-}2$$

Where:

P$_n$:" total installed lighting power in the room or zone" is the power of all luminaires in the considered room or zone.

F$_C$: "costant illuminance factor" is the factor relating to the usage of the total installed power when constant illuminance control is in operation in the room zone.

t$_D$: "daylight time usage" is the operating hours during the daylight time, measured in hours

F$_o$: "occupancy dependency factor" is the factor relating the usage of the total installed lighting power to occupancy period in the room or zone.

F$_D$: "daylight dependency factor" is the factor relating the usage of the total installed lighting power to daylight availability in the room or zone

An estimate of the parasitic energy (W$_{p,t}$) required to provide charging energy for emergency lighting and for standby energy for lighting controls in the building shall be established using the equation:

$$W_{P,t} = \sum \left\{ \left\{ P_{pc} \times \left[\left(t_y - \left(t_D + t_N \right) \right) \right] \right\} + \left(P_{em} \times t_N \right) \right\} / 1000 \qquad [kWh] \qquad 5\text{-}3$$

In this equation it is not included the power consumed by a central battery emergency lighting system.

Ppc: "total installed parasitic power of the controls in the room or zone" is the input power of all control systems in luminaires in the room or zone, measured in watts

P$_{em}$: "total installed charging power of the emergency lighting luminaires in the room or zone" is the input charging power of all emergency lighting luminaires in the room or zone, measured in watts

t_y :"standard year time" is the time taken for one standard year to pass, taken as 8 760 h

t_N :"non-daylight time usage" is the operating hours during the non-daylight time, measured in hours

te : "emergency lighting charge time" is the operating hours during which the emergency lighting batteries are being charged in hours

t_s : "scene setting operation fime" is the operating hours of the scene setting controls in hours

The total lighting energy can be estimated for any required period t (hourly, daily, weekly, monthly or annually) in accordance with the time interval of the dependency factors used. This estimation does not include the power consumed by control systems remote from the luminaire and not drawing power from the luminaire. Where known this should be added.

In the case of existing buildings, W_{pt} and $W_{Lt,}$ can be established more accurately by directly and separately metering the energy supplied to the lighting.

5.2.3.2   _Total annual energy used for lighting_

$$W = W_L + W_P \qquad [kWh]$$

5-4

Where:

An estimate of the annual lighting energy required to fulfil the illumination function and purpose in the building (WL) and annual parasitic energy (WP) required to provide charging energy for emergency lighting and for standby energy for lighting controls in the building shall be established by equations 6-2 and 6-3 respectively.

5.2.3.2.1   _Lighting energy numeric indicator (LENI)_

Lighting Energy Numeric Indicator for the building

LENI = W/A   [kWh/(m^{2}year)]

5-5

Where:

W is the total annual energy used for lighting [kWh/year]

A is the total useful floor area of the building [m^2]

5.2.4.   **Installed lighting power**

There are two forms of installed power in buildings, luminaire power and parasitic power.

Luminaire power, which provides power for functional illumination conforming to EN 12193 for lighting of Sports facilities and EN 12464-1 for lighting of Indoor work places.

Parasitic power, which provides power for lighting control systems and for charging batteries foremergency lighting in conformance with EN 1838.

5.2.5.   **Calculation methods**

5.2.5.1   *Quick method*

When using the quick method of estimation of the annual lighting energy estimation for typical building types equation 6-4 shall be used.

The energy requirement estimation by the Quick method will yield higher LENI values than that obtained by the more accurate Comprehensive method. The default values for t_D, t_N, F_c, F_D, F_O and W_P are given in Annex E, F and G of the standard.

5.2.5.2   *Comprehensive method*

The comprehensive method allows for a more accurate determination of the lighting energy estimations for different periods e.g. annual or monthly. When using the comprehensive method of lighting energy estimations equation 6-2 shall be used for the required period t.

The determination of the daylight dependency factor (F_D) for a room or zone is described in Annex C of the standard and the determination of the occupancy dependency factor (F_O) for a room or zone is described in Annex D of the standard This method may be used for any periods and for any locations provided that the full estimation of occupancy and daylight availability is predicted.

5.2.6. Benchmark values and lighting criteria

In the assnex F of the standard banchmarck values for several kind of installation are given. According to table F1 of the standard for office environment are given the following values:

Benchmark values and lighting design criteria
Table F.1 — Bench mark default value

	Qual. class	Parasitic Emergency kWh/(m²/year)	Parasitic Control kWh/(m²/year)	PN W/m²	t_O h	t_N h	F_c no cte illiminance	F_c cte illiminance	F_o Manu	F_o Auto	F_D Manu	F_D Auto	LENI no Limiting value Manu kWh/(m²/year)	LENI no Auto	LENI cte illiminance Limiting value Manu kWh/(m²/year)	LENI cte illiminance Auto
Office	*	1	5	15	2250	250	1	0.9	1	0.9	1	0.9	42.1	35.3	38.3	32.2
	**	1	5	20	2250	250	1	0.9	1	0.9	1	0.9	54.6	45.5	49.6	41.4
	***	1	5	25	2250	250	1	0.9	1	0.9	1	0.9	67.1	55.8	60.8	50.6
Education	*	1	5	15	1800	200	1	0.9	1	0.9	1	0.8	34.9	27.0	31.9	24.8
	**	1	5	20	1800	200	1	0.9	1	0.9	1	0.8	44.9	34.4	40.9	31.4
	***	1	5	25	1800	200	1	0.9	1	1	1	0.9	54.9	41.8	49.9	38.1
Hotel	*	1	5	10	3000	2000	1	0.9	0.7	0.7	1	1	38.1	38.1	34.6	34.6
	**	1	5	20	3000	2000	1	0.9	0.7	0.7	1	1	72.1	72.1	65.1	65.1
	***	1	5	30	3000	2000	1	0.9	0.7	0.7	1	1	108.1	108.1	97.6	97.6
Hospital	*	1	5	15	3000	2000	1	0.9	0.9	0.8	1	0.8	70.6	55.9	63.9	50.7
	**	1	5	25	3000	2000	1	0.9	0.9	0.8	1	0.8	115.6	91.1	104.4	82.3
	***	1	5	35	3000	2000	1	0.9	0.9	0.8	1	0.8	160.6	126.3	144.9	114.0
Restaurant	*	1	5	10	1250	1250	1	0.9	1	1	1	-	29.6	-	27.1	-
	**	1	5	25	1250	1250	1	0.9	1	1	1	-	67.1	-	60.8	-
	***	1	5	35	1250	1250	1	0.9	1	1	1	-	92.1	-	83.3	-
Sport places	*	1	5	10	2000	2000	1	0.9	1	1	1	0.9	43.7	41.7	39.7	37.9
	**	1	5	20	2000	2000	1	0.9	1	1	1	0.9	83.7	79.7	75.7	72.1
	***	1	5	30	2000	2000	1	0.9	1	1	1	0.9	123.7	117.7	111.7	106.3
Retail	*	1	5	15	3000	2000	1	0.9	1	1	1	-	78.1	-	70.6	-
	**	1	5	25	3000	2000	1	0.9	1	1	1	-	128.1	-	115.6	-
	***	1	5	35	3000	2000	1	0.9	1	1	1	-	178.1	-	160.6	-
Manufacture	*	1	5	10	2500	1500	1	0.9	1	1	1	0.9	43.7	41.2	39.7	37.5
	**	1	5	20	2500	1500	1	0.9	1	1	1	0.9	83.7	78.7	75.7	71.2
	***	1	5	30	2500	1500	1	0.9	1	1	1	0.9	123.7	116.2	111.7	1.5.0

Figure 5-20 Benchmark values

6.   Office ergonomics and office environment

6.1.   Introduction

Vision is the most important of all the five senses – and the one we rely on most heavily at work. So correct workplace lighting is a matter of particular importance. As numerous scientific studies have shown, close links exist between the quality of lighting on the one hand and productivity, motivation and well-being on the other. In the modern working world, however, we need more than just the right amount of light for workplace tasks. We need a succession of stimulating and relaxing situations throughout the day. So creating different lighting scenes in rooms with different functions (workrooms, meeting rooms, recreation/regeneration zones) helps boost motivation and promote a sense of well-being.

6.2.   Office Environment

Nothing in the working world has undergone such a radical transformation in recent years as office work. With rapid advances in information and communication technologies, corporate structures in a state of flux and totally new forms of work emerging, today's world of work is a world of computers and networks, workflow and data exchange. Office work has become information and communication work. But changes in the way we work also impact on other areas of our private and working lives. The knowledge society of the 21st Century needs different offices, differently designed buildings, even different urban design. The industrial kind of office work, where people streamed to their cellular offices in the morning and streamed back to their homes outside the town or city centre in the evening, is being replaced by new, flexible, personalized working arrangements. The traditional form of office work, where each employee performs one operation at his or her desk, has been superseded in many modern companies and organizations by more efficient forms of work such as project-oriented teamwork. Here, specialized team workers meet at various locations in various constellations for limited sessions of cooperation. Their office equipment consists of mobile phone, laptop computer and PDA (Personal Digital Assistant) and they decide for themselves where, when and with whom they work. Flexible

working times and flexible work locations, non territorial offices and mobile workstations present new architectural requirements for the places where we work. Individual work is done at home in a home office or at customers' premises, in combi offices or in a recreation zone. Company buildings are thus becoming communication centers, places for employees to meet and exchange information. Key facilities here are conference zones, conference rooms and cafeterias – places where teams can come together for formal or informal meetings. The "office building" system as a whole has thus clearly become more complex. What is more, employers increasingly insist on company buildings being designed to make a cohesive visual statement in tune with the organization's corporate design. From facade to reception area, cellular office to combi office, executive office to office areas open to the public, every element needs to suit the company's style. The architect thus becomes an all-rounder, designing color schemes and furnishings, lighting and air-conditioning as elements of an integrated system. The primary gearing of that system, however, is dictated by the need to ensure efficient organization of labour. Above all, employees need a motivating, performance-enhancing atmosphere, which is now widely known to be promoted by an agreeable working environment. In short, the challenge lies in creating an ambient for work which is both functional and agreeable. A major role here is played by correct lighting. This forms an important part of the office building system as a whole because it paves the way for good visual performance and comfort at work and significantly affects the way we respond to the architecture of the building and the interiors. In modern forms of office, rigid room and workplace structures are being superseded by flexible and requirement- oriented concepts of use. In many cases, a kind of nomadic culture prevails, with employees able to use any workplace. These calls for new room architecture and more flexible furnishings: freely re-arrangeable room structures, individually adjustable desks and office chairs, and variable lighting systems. Just as the way we work has been transformed, so too has the design of the rooms in which we work become more complex and diverse. The activities performed in offices today range from graphic design work on a VDU to multimedia presentations for colleagues and clients. Regardless of the way offices are used, they can be divided into four basic types: the cellular office, the group office, the combi office and the open plan office. The most important form of office at present is the traditional cellular office. According to a study conducted by the Dresdner Bank Property Group, 80.7% of all offices conform to this type. In the

years ahead, however, we will see a dramatic decline in its significance. New flexible forms of office, such as the combi office or the flexspace (flexibly adaptable) office will be the norm in the working world of the future. Production processes and building design, work hierarchies and room layouts, responsibilities and types of room – in the future, virtually no aspect of office work or its architecture will remain as it is today. Even the role of lighting will be reviewed. In the past, the primary purpose of office windows was to admit natural light and provide a visual link with the outside world; artificial lighting generally consisted of fixed luminaires arranged in line with the axes of the building. This arrangement then determined the positioning of workplaces in the room – and a central light switch permitted a choice between light and darkness. In recent years, the design of all lighting components has become much more sophisticated. Regulating the daylight that enters a room – e.g. through the use of facade elements or window blinds makes for better air conditioning, reduces artificial lighting costs, promotes a greater sense of well-being and thus heightens the motivation and operational efficiency of personnel. Artificial lighting is seen as an architectural element. Lamps and luminaires are smaller and more efficient, they blend discreetly with the architecture or they strengthen its statement through their own design. Today, a variety of types of lighting are available to cater for every office activity and room situation. For example: direct/indirect luminaires with variable intensity distribution curves for agreeable ceiling illumination and glare-free workplace lighting, or flexible combinations of standard and desktop luminaires which move with desks. Lighting control is a core element of any building management system. Central and local regulation of communications, air-conditioning, daylight control and artificial lighting systems makes building management more efficient and boosts productivity. Modern lighting control systems are designed for daylight-dependent and presence dependent regulation permit numerous lighting scenes and offer a high degree of operator convenience. To ensure the right standard of lighting for a specific room use, the right balance needs to be struck between visual performance, visual comfort and visual ambience. The emphasis may need to be on:

- visual performance, which is primarily defined by lighting level and glare limitation,

- visual comfort, which depends mainly on colour rendering and harmonious brightness distribution,

- visual ambience, which is essentially influenced by light colour, direction of light and modelling.

6.3.   Office Ergonomics

The variety of office type require a deeper designer knowledge regarding a wide range of multidisciplinary aspects according to the continuous development due to the steady introduction of new technologies in the work process and to on the growth of user's needs. (Figure 6-1)
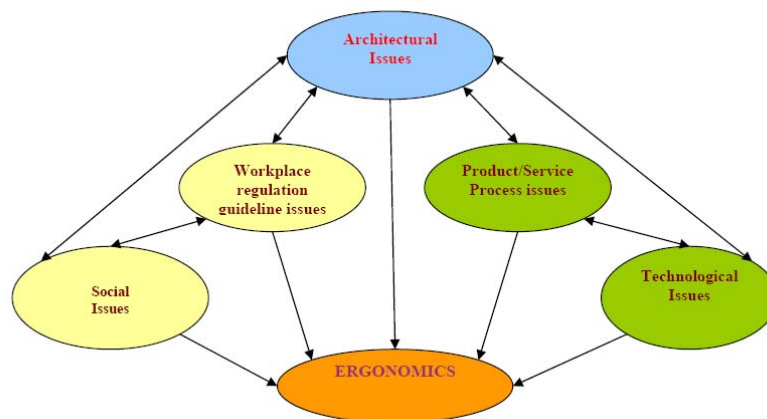
Figure 6-1 Aspects of the ergonomy

It's not possible to expect a similarity between different concepts regarding different requirements of flexibility, of the involved technologies and also all the specific factors that should be fulfilled to satisfy every peculiar needs of the user. Ergonomics is the matching of the work environment, tools, and the people who use them. Good ergonomics promotes productivity, minimizes physical distractions, and reduces the risk of injury and illness. Unlike many occupational safety and health issues, ergonomic considerations vary highly with the person, his or her physical characteristics and preferred working style. Ergonomics is the scientific study of the human at work. It considers the physical and mental

capabilities and limits of the worker as he or she interacts with tools, equipment, work methods, task and working environment. Office ergonomics is the branch of ergonomics dealing specifically with the office environment. In recent years the main focus of office ergonomics has been on computer work due to the rapid increase in computer use in the modern office and the associated increase in injuries. More interesting for the topic of that research are the ergonomic issues that should be taken in consideration for a correct planning of the office environment.

Issues	AI	WR	PPI	SI	TI
Good work structure	Influent	Barely influent	Very influent	Influent	Barely influent
Good social structure	Very influent	Not influent	Influent	Very influent	Not influent
Quiet and undisturbed workplace	Very influent	Not influent	Influent	Influent	Not influent
Functional workplace	Very influent	Influent	Barely influent	Not influent	Very influent
Possibility of relax	Very influent	Influent	Barely influent	Very influent	Not influent
Possibility of recreation	Very influent	Influent	Barely influent	Very influent	Not influent
Good communication structure	Very influent	Barely influent	Very influent	Very influent	Very influent
Good space structure	Very influent	Barely influent	Very influent	Very influent	Not influent
Possibility of different posture on the workplace	Barely influent	Very influent	Barely influent	Not influent	Not influent
Human and professional appreciation	Not influent	Not influent	Very influent	Very influent	Not influent

Legend: Very influent (red), Influent (orange), Barely influent (yellow), Not influent (cyan)

Figure 6-2 Ergonomic Issues: AI architectural issues, WR Work regulation issues, PI product (or service) process issues, SI social issues, TI technological issues;

### 6.3.1.	Office structure

Ergonomics deals with many issues, starting with a single employee and their workstation, and expanding out to include an entire department. Most of the organizational and environmental factors, as well as the selection of workstation furniture, are under management control. Many of the factors related to the arrangement of the workstation and work habits are under each employee's control. The focus of ergonomics is always on designing for the individual employee, who brings unique characteristics with her or him to the job. Some of these characteristics, such as height and age, cannot be changed, while others, such as training and experience, can be changed. The first step in implementing ergonomics in the office is to analyze the work being done, whether we are looking at a single workstation or the entire department. So it is really important to fix the limits of the field that we will study according with the scope of our work the aim of this section is not to produce a comprehensive study on the office ergonomics, but rather to understand which are the characteristics of ergonomics that affects the lighting quality in office environment. After this consideration we can start to define the limits of our investigation. Let's take in consideration the different areas of the office ergonomics and to point out witch aspects will be taken in consideration. Figure 6-4 shows different design criteria that should be taken in consideration investigating the best ergonomic solution. Those criteria derive from standards, recommendations and guidelines for workplaces.
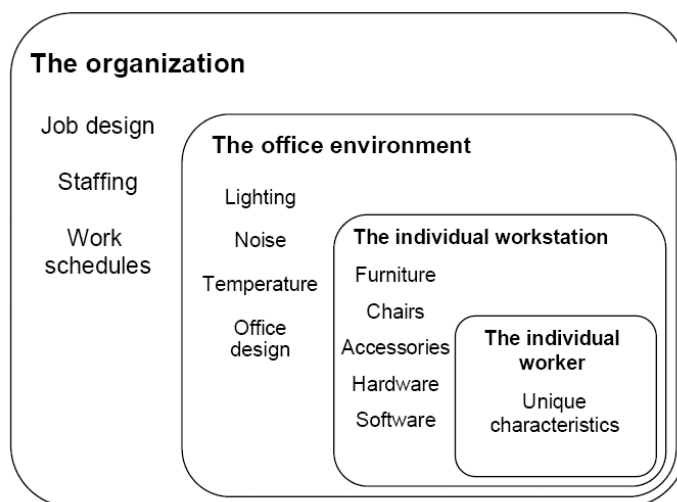
Figure 6-3 Office Ergonomics: office environment structure.

6.3.1.1   *The organisation*

The organisation is the more general aspect of the office structure. This aspect defines generally the service or production process taking place in the office, defines the Staff structure and the work organisation. The components that define the organisation are:

- Job design: give us the information concerning the activities and about the tasks that will be carried out in the office.

- Staffing: give us the information about the structure of the staff and about how is the process structure. Moreover are important all the information about the work style and the communication level that is required in the work process

- Work schedules: give us information about the duration of the office activities.

- Those information are necessary to understand witch type of office is needed to decide how should be the office lay-out and the arrangement of the spaces.

6.3.1.2   *The office environment*

The office environment take in consideration all the environmetal aspects in the office planning like:

- Lighting: take in consideration all the issues concerning the illumination of the spaces

- Acoustic: take in consideration all the issues concerning the noise reduction within the spaces

- Thermal comfort: take in consideration all the Thermo-hygrometric issues

- Office design: take in consideration al the issues regarding the organization of the spaces.

The purpose of this study are the lighting issues and overall the problematic concerning the quality of the lighting. According to our study the Acoustics issues and the Thermal comfort issues are irrelevant. The office design should however taken in consideration because con be relevant for the achievement the lighting results.

6.3.1.3   The individual workstation

The individual workstation is the most investigated field within ergonomics. Object of the investigation are all the issues regarding the correct posture of the workers the health problems linked with the position of the several tools used and habits of the workers. All those issues are not taken in consideration in our investigation because they didn't affect directly the lighting issues.

Criteria	Details	Requirements	Source
Workstation	Personal user's work station (Genera use)	Minimum work surface of 1,28 m^2 equivalent with a table 1,60x0,8. The work surfaces should have a height of 0,8m. Suggested work surface with an area of 2 x 0,90 m.	DIN 4543 part 1
Surfaces	Reflection grade	Ceiling: 70-85% ; Walls: 50%-65%; Floor: 20%-40%	DIN 5035 DIN 66234
Rooms area	Average area	Rooms under 8 m^2 can not be used as workplaces Office workplace (normal): 8-10 m^2 Office workplaces (with VDU): 10-12m^2	ZH1/535 sec. 4.10.1
Room height		0-50 m^2 : 250 cm 50-100 m^2 : 275 cm 100-2000 m^2 : 300 cm >2000 m^2 : 325 cm	§23 ArbStättV
Acoustics Air volume Thermal Comfort	Per user Only For office	Suggested value 35-45db 12m^2-18m^2 20 C	DIN EN ISO 9241-6 §23 ArbstättV ISO 7730

Figure 6-4 Office Design Criteria

6.3.2.   Requirements

6.3.2.1   User's general requirements

The basic requirement that should be satisfied for any user are:

- Good work structure

- Good social structure

- Quiet and undisturbed workplace

- Functional workplace

- Possibility of relax

- Possibility of recreation

- Good communication structure

- Good space structure

- Possibility of different posture on the workplace

- Human and professional appreciation

These requirements have a certain correlation to the issues shown in Figure 6-2. How important is that correlation can be different from case to case but is anyway important trying to understand how strong this relationship is and how much the fulfillment of those issues depends on the fulfillment of those requirements.

6.3.2.2 *Single user requirements*

More precise consideration should be made, for each case study, for all the factors that influence directly the single operator's task like:

- Work task

- Work structure

- Access to technology

- Type of office

- Furniture/workplace lay out

6.3.2.3 *Office environment requirements*

Moreover should be taken in consideration all those factors that characterize the work environment like:

- Thermal comfort

- Acoustics

- Illumination

6.4. Office Types

6.4.1. Communication and office type

A fundamental goal is to develop an ergonomic solution for the office spaces able to fulfill the needs of communication between the operators, according with the dynamics work activities, and to safeguard discretion and concentration of the operators not involved in the communication dynamics. The higher is the need to switch between communication and concentration the higher should be the flexibility of the environment. In Figure 6-5 s represented a classification of the office typology according to several issues like communication, mobility, utilization.
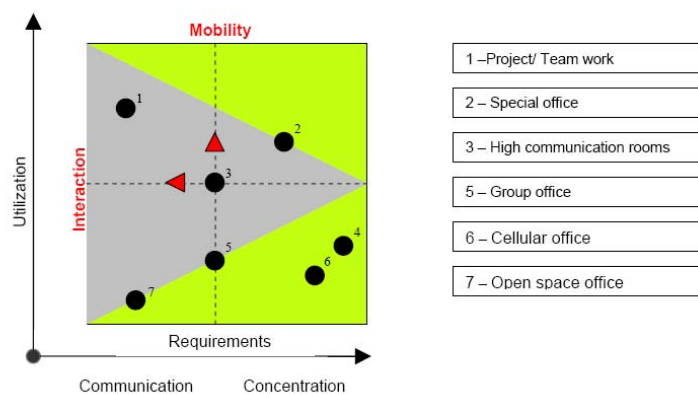
Figure 6-5 Classification of office type according with the utilization, the requirements, the interaction and the mobility issues.

6.4.2. Cellular offices

The cellular office is the type of office traditionally used to accommodate a maximum of six office workers – and it is still the best solution for personnel who predominantly perform tasks which require concentration, a personal archive of files and books or the privacy needed for confidential conversations with clients or staff. It is also ideal for small groups of two to three people who work together as a team and constantly need to exchange information about their work. Despite its structural limitations, the cellular office is very popular with most office workers. For many, the high degree of privacy, the proximity of windows and the

possibility of tailoring the room, its climate and its lighting to personal tastes outweigh the disadvantages. The lack of interaction with a larger group needs to be made up in other ways here, e.g. in meetings. Cellular offices are put to many different uses. They accommodate scientists and section leaders, secretaries and designers; they are used for VDU work and team meetings, concentrated study and appointments with clients. The diversity of room use is reflected accordingly in a wide range of room shapes, furnishings, color schemes, etc. The type of lighting required depends on the structure of the room, the use or uses to which it is put and the atmosphere that needs to be created. In most cellular offices, louvered recessed luminaires are the option most widely preferred. Louvered luminaires suitably glare suppressed for direct lighting are an economical solution for many applications, also providing good conditions for VDU work. A more agreeable and more motivating impression is made by a room where pendant luminaires for direct/indirect lighting are used. By illuminating the ceiling, these avoid a "cave effect" even in small offices, achieve a more natural distribution of brightness and give the room a more homely appearance. For meetings especially, direct/ indirect lighting systems generate a better visual ambience because light and shade are more balanced and faces look more natural. Standard luminaires add a prestigious note to cellular offices. As direct/indirect lighting systems, they offer all the advantages mentioned above but can additionally enhance the room architecture through their design. In conjunction with desktop luminaires, the room and the work surface on the desk are equally well illuminated. Another important advantage is flexibility, because even today one in four company employees changes offices at least once a year. A lighting system consisting of standard and desktop luminaires can move with a relocating employee without ceiling and electrical installations having to be touched. For vertical surfaces where reading tasks are performed, e.g. at cabinets, shelving systems, wall charts, maps, supplementary lighting is needed. Even though light switches are normally within easy reach in cellular offices, lighting control systems have distinct advantages. Conferences and group communication often take place outside the cellular office, which then stands empty, so presence dependent control is a practical and convenient addition to the lighting system. Other economic and logistical advantages are provided by central control systems which check if office lights have been switched off in the evening and whether lamps need to be replaced.

6.4.3. Group office

The group office emerged as an initial response to the new forms of work that heralded the age of communication. It made its appearance in the late 1970s and early 1980s when offices started to become computerised and office work was transformed as a result. The rigid departmental groupings of the open plan office were replaced by smaller units which could work more closely and effectively as teams. In the 1990s, architects looked at the down-scaled open plan offices again and developed new ideas for group or team offices. Monotonous arrangements of desks designed solely to make efficient use of space were superseded by zonal concepts. Owing to its comfortable size, flexible design and effective communication structure, the group office is still a popular office and work concept even today. It avoids the anonymity of the open plan office and provides good conditions for direct personal teamwork in established groups of 8 to 25 employees. One central issue in the context of group office lighting is daylight control. Where rooms are seven to eight meters deep, special light-reflecting window blinds can usefully direct available daylight to the parts of the room farthest from windows. But adequate daylight is not always available, so workplaces located deep in the room still need to be illuminated by artificial light sources. In the classic setup, desks are positioned one behind the other at right angles to the window wall. Daylight then falls on desktops and workstations from the side, with window glare eliminated by blinds. The artificial lighting units – e.g. louvered luminaires for direct lighting – are mounted parallel to the window wall to provide effective task area illumination. Other lighting concepts permit a free and flexible arrangement of workplaces. For workplace clusters – i.e. relatively small groups of desks – pendant luminaires for direct/indirect lighting generally yield better results. Owing to the brightness of the ceiling, the lighting looks more natural, dazzling reflections on work materials and screen are reduced, and the better modelling makes faces and objects look more appealing. For a more flexible workplace arrangement, direct/indirect standard luminaires can be used in combination with desktop luminaires. Vertical surfaces where reading tasks are performed – at cabinets, shelving systems, wall charts, maps, etc. – call for adequate supplementary lighting. To give a group office an energizing, motivating atmosphere without compromising on clarity of structure, the lighting should emphasize the zonal layout of the room. Downlights, for example, can be used to provide agreeable, non-directional lighting for service centers, where documents

are faxed or copied. Where these facilities are located at the perimeter of the room, indirect wall luminaires are another option. In conference zones, direct/indirect luminaires should be used wherever possible to ensure natural modelling for faces and work materials. In regeneration zones, light colours should be warm, e.g. provided by luminaires in an indirect trunking system supplemented by table luminaires for reading tasks.

6.4.4. Combi offices

In the office buildings of the information society, the efficiency and success of employees depends to a large extent on communication. In many cases, employees work on successive projects in a team, with each team member addressing a special assignment relating to the project. The concentrated work of the individual is thus performed in constant consultation with the team. The combi office is an architectural response to this way of working. It permits a connection between the open communication of the team and the individual work of the team members. The combi office thus combines team spirit and communication, transparency and flexibility. Structurally, a combi office is like a marketplace: a communal space surrounded by individual "houses". A marketplace provides a platform for the public exchange of information and trade in goods. The houses around it are where the information is processed and the products manufactured. In the same way, the individual workrooms of a combi office can also be seen as production sites. They are where parts of the project are crafted in concentrated individual work. The fruit of that labor is taken to the adjacent communal zone, where the various parts of the project are put together by the team. But the communal zone performs other vital functions as well. It is both a communication and a supply centre – accommodating not just the zones for team meetings but also photocopiers and fax machines, files, records and shared information resources, such as periodicals and reference works. Lighting for a combi office should also be modelled on the concept of the marketplace and provide zonal lighting wired for individual control. In the workrooms in particular, it must be remembered that "production work" is very diverse, ranging from reading project papers to performing graphic design work at a VDU, to holding small informal meetings at the workplace. A bright, agreeable atmosphere is created by direct/indirect pendant luminaires or standard luminaires. Dimmable luminaires, supplemented by desktop luminaires at the workplace, permit individual lighting

scenes. As most offices have relatively large windows, the use of lighting control systems permitting daylight-dependent regulation of the general lighting is recommended. For vertical surfaces where reading tasks are performed – e.g. at cabinets, shelving systems, wall charts and maps – adequate supplementary lighting is required. In the communal room, the lighting should be designed to enhance spatial clarity by differentiating between zones. This helps identify the various function zones of the "marketplace" and enables lighting to be tailored to the relevant visual tasks. Direct/indirect pendant luminaires over conference zones create an agreeable ambiente in which faces and work materials can be clearly identified. For temporary workplaces and reading areas in the communal room, direct/ indirect standard luminaires – possibly regulable models – are a flexible solution. For optical emphasis and differentiation of the individual zones, downlights are a suitable choice. They also provide effective guidance through the room. For the general lighting in the communal room, economical louvered luminaires with good glare suppression offer a high degree of visual comfort.

6.4.5. Open Space office

For quite some time, open plan offices have been experiencing a renaissance. The functional and flexible structuring they permit makes them an attractive option for many company operations where efficient room use is a must. Their popularity has been boosted, in particular, by the rapid spread of call centres. Nearly 200,000 people in Germany work in this sector alone. Modern open plan offices are still very much geared to VDU work; most of the activities performed in them consist of computerized tasks requiring concentration. Communication in an open plan office is mostly telecommunication, i.e. telephone communication with customers or outfield colleagues. In today's open plan offices, one finds many "clusters" of workplaces, where teams work together. Workplace arrangements here can vary considerably, from strict geometrical patterns to circular office landscapes With computer workplaces, it is essential to ensure that the strain on the eyes from switching constantly back and forth between screen, work materials and surroundings is kept to a minimum and that the need for strenuous accommodation and adaptation is avoided. So monitors and any papers the operator needs to consult should be the same distance from the eye, 40 to 80 cm. It is also important to avoid direct and reflected glare. Direct glare occurs as a result of excessively high luminance contrast, e.g. where a VDU is positioned directly in front of a window. Reflected glare results from bright surfaces, such as windows or luminaires, being reflected on screens. Where these sources of disturbance are not adequately limited, fatigue, underperformance and personnel health problems result. It is important, therefore, that VDUs should be arranged in relation to windows or shielded by curtains or blinds in such a way that glare is avoided. Room-dividers or cabinet partitions can help make glare suppression measures more effective. For the lighting designer, this means meeting a number of specific requirements. First, account needs to be taken of the insular character of the team clusters. A variety of modern direct/indirect pendant luminaires specially developed for VDU work are available for workgroup lighting in open plan offices. For vertical surfaces where reading tasks are performed, e.g. at cabinets, shelving systems, wall charts or maps, adequate supplementary lighting is required. The challenge does not end with work zone lighting, however. Communication and perimeter zones also require attention. Conference and reception zones lend structure to the room and call for varied lighting to

emphasize their special character and facilitate orientation in the room as a whole. Bright perimeter zones, e.g. walls illuminated by wallwashers, make the room look larger. In open plan offices in particular, user comfort can be significantly enhanced by lighting control systems. And as such offices frequently have long rows of windows, considerable room depths and various types of lighting, daylight-dependent regulation of window blinds and individual room lighting elements may also be considered.

6.4.6.   Prestige office

As the name indicates, a prestige office underlines the stature of the company and the individual to whom it is assigned. Its interior design should reflect the identity of the company or the personality of the occupant. This is where prestige offices get their atmosphere, which can range from cool and businesslike to light and experimental, to uncompromisingly sumptuous. Most prestige offices consist of three zones, each with a clear purpose: first the workplace, where a variety of tasks are performed and VDU work plays only a minor role; secondly a conference zone, designed to cater for small group meetings; and thirdly a "presentation zone", where the company presents its corporate culture and its work. The three room zones share a uniform atmosphere, although each zone has its own function and mood. The atmosphere needs to be appropriate for the statement which the room is supposed to make; in most cases, a cheerful homely atmosphere is required. In offices with a relatively dark colour scheme and lots of wood finishes, this is best supported by soft indirect lighting and warm light colours. At the workplace, there is normally no need for purely functional lighting. On the contrary, the lighting should be part of the architecture and designed to cater for a variety of visual tasks. Standard and desktop luminaires or pendant luminaires of decorative, futuristic or purist design are suitable options. What is important is that the lighting is bright enough for all visual tasks, glare due to windows and luminaires is avoided and the distribution of light at the workplace and throughout the room is harmonious. Marked differences in brightness along different lines of sight make it harder for the eye to adapt and give rise to fatigue. For vertical surfaces where reading tasks are performed -e.g. at cabinets, shelving systems, wall charts or maps – adequate supplementary lighting is required. In the conference zone, lighting should be low-key to permit full concentration on the persons present. Balanced modelling and warm light colours

help give faces a more natural and agreeable appearance. Direct/in direct luminaires fitted with warm tone lamps provide the high vertical illuminance required and cast a soft, pleasant light. Glare due to direct lighting or reflections needs to be avoided, as does a marked contrast in brightness with the surroundings. Both are distracting and cause visual fatigue; concentration and motivation suffer. In the third room zone, the presentation zone, attention needs to be directed to objects or images. At the same time, the presentation zone must be neither too bright nor too dark in relation to the rest of the room; direction of light and modelling must be designed to ensure that three-dimensional objects are identifiable as such. Downlights, wallwashers and a variety of spots can be an effective accentuating lighting solution here. In view of the many different types of lighting used in most prestige offices, a programmable lighting control system makes good sense. Pre-defined lighting scenes for concentrated work at the desk, meetings with colleagues or the reception of guests help ensure balanced lighting in the room and permit a comfortable lighting atmosphere for the situation required.

6.4.7. CAD office

From a lighting viewpoint, computer-aided design is one of the most demanding office activities of all. Characters and symbols, super-fine lines and patches of varying contrast and colour call for intense concentration and perfect visual clarity of screen displays, work materials and other objects. So special attention needs to be paid in CAD offices to ergonomic workplace design. Room and workplace lighting plays an important role in ergonomic design. Lighting levels need to be chosen to ensure a balance between the brightness of VDU screen, task area and surroundings. Changing visual tasks – i.e. working on screen, executing sketches on light-coloured paper and making visual contact with colleagues in the room – call for harmonious luminance distribution. Direct and reflected glare needs to be limited. Direct glare is caused by bright surfaces, such as windows, or unshielded lamps; reflected glare is caused by light reflections on glossy paper or screens. Direct and reflected glare cause extreme differences in luminance and impair visual conditions, thus undermining office workers' sense of well-being and ability to concentrate on the task in hand. To ensure good visual performance, a classic arrangement of workplaces at right angles to the window wall is recommended, with desks for ancillary design operations positioned near the window and CAD workstations located nearer the middle of the room. Daylight then falls on desks from the side and glare is largely eliminated. Luminaires should be installed parallel to the window wall. High-grade specular louver luminaires with specially designed louvers ensure glare-free lighting at the workplace. Adequate daylight is not always available, so luminaires should be positioned to the left and right of the desks. The direction of light and modelling thus achieved permits paperwork and objects to be viewed without undue risk of fatigue. As for types of lighting, direct/ indirect luminaires offer the highest degree of comfort. A bright ceiling makes for balanced luminance distribution, giving the room lighting a more natural and more motivating impact. Supplementary desktop luminaires enable the lighting to be tailored to individual work situations. In aisles, louvered luminaires, downlights or direct/ indirect wall luminaires are a suitable option. What is particularly important in CAD offices is modern lighting control. For one thing, the lighting level at each individual workplace needs to be adjustable for different tasks because while a great deal of light is needed for studying technical drawings on paper, VDU work often calls for dimming.

Secondly, uniformity of lighting needs to be right at all times of day. Where incident daylight at desks is intense, both the German national ordinance protecting employees working at VDUs and EU Directive 90/270 stipulate that window-blinds must be provided for screening and supplemented, if necessary, by artificial lighting. For vertical surfaces where reading tasks are performed – e.g. at cabinets, shelving systems, wall charts or maps – adequate supplementary lighting is required.

6.4.8. Office open to the public

Despite Internet and email, personal contacts more important than ever for many companies and organisations today. Customers, clients and members of the public want personalized advice and wish to meet the people they deal with face to face. In much of the private sector, an invitation to visit the company in person is an important part of customer bonding and a good opportunity to promote image and product range. Classic service halls, with their cold stone floors and high ceilings, are being relegated to the past. The preference today is for a more homely atmosphere, with warm colours, small room units and a consulting zone that has shifted from the counter to niches or desks. As in all relatively large interiors, the lighting concept here needs to reflect the structure of the room, with its various zones for different tasks. Visitors entering the room want to be able to identify clearly where they need to go. Bright reception areas and illuminated information panels facilitate initial orientation and direct visitors' attention. To avoid cave effects in an entrance area, room lighting and ceiling illumination need to be adequately bright. An interesting effect is achieved with louvered luminaires or downlights in the ceiling and indirect ceiling floodlights mounted on walls or pillars. Large luminous ceilings or direct/ indirect pendant luminaires also create an agreeable and natural atmosphere. In interview niches and at consultants' desks, the lighting needs to be suitable for both communication situations and VDU work. Where room layouts frequently change, the lighting needs to be equally flexible. Desktop luminaires and standard luminaires for direct/indirect lighting can be repositioned at any time and, where ceilings are bright and a normal height, create lighting conditions which permit high visual comfort for interviews and good visual performance for VDU work. For vertical surfaces where reading tasks are performed – at cabinets, shelving systems, wall charts, maps, etc. – adequate supplementary lighting is required. Offices which are open

to the public also perform a representative function, so attention needs to be paid not only to the functional design of the lighting but also to its visual appeal and aesthetic impact. Even with the most impressive architecture, however, that impact can only be achieved if the right light is provided at the right place. Recessed floor luminaires and downlights vividly emphasise pillars; spots cast selected zones in a dramatic light or imbue presentation areas for images and artworks with visual tension. For the public, good and exciting lighting design brings a room and its architecture to life.

6.4.9. Reception rooms / reception areas

Entrance areas make a first and crucial impression on visitors. Architecture and dimensions, materials and furniture, lighting and acoustics – they all combine to form an "image" the moment the visitor enters the room. For every visitor, the entrance area is the point of initial contact, the beginning of all communication with their host. Entrance areas generally consist of four zones: the actual entrance, the reception area, the lobby and the areas leading into the building. So the primary task for architect and lighting designer is to identify these zones and provide clear aids to orientation for the visitor. The entrance links the outdoor areas with the interior of the building. This is where the visitor steps out of the daylight into the building. As the human eye takes time to adapt from the bright daylight outdoors to the lower lighting indoors, entrances need to be particularly bright. Adaptation is facilitated by large windows and glare-free lighting of high luminous intensity in this area. A daylight- dependent lighting control system should adjust the artificial lighting in line with the level of available daylight. Steps or stairs in this area need to be particularly well identified and illuminated. Most visitors first make their way to the reception desk, so this needs to be clearly identifiable as such. Supplementary lighting provided for a reception area and any vertical information panels makes these stand out against the surroundings and helps visitors find their way. A cheerful, inviting atmosphere is generated by harmonious brightness distribution with anti-glare lighting for counters and signs as well as warm light colours. The lobby area is a place for communication, a place where visitors are greeted. The purpose of lighting here is to create a visual ambience where people – and especially people's faces – can be clearly recognized. Highly directional lighting should be avoided because it casts unfavorable shadows. Direct/ indirect lighting with warm light colours ensures a

balanced distribution of light and helps create a positive atmosphere for communication. Corridors, staircases or lifts connect the entrance area with the interior of the building. Here, too, lighting can facilitate visitor orientation, e.g. in route guidance systems incorporating coloured LED luminaires. A clear light guidance system points visitors in the right direction and bright display panels or backlit signs provide information. Corridors and staircases can appear intimidating if they are much darker than the entrance area. To avoid this tunnel effect, care must be taken to ensure uniform or gradually decreasing brightness. For staircases especially, glare-free lighting is essential on the stairs. Safety can be heightened by modern LED modules integrated into the stairs or recessed wall luminaires illuminating the treads. In entrance areas with large windows, a daylight-dependent lighting control system for the artificial lighting is a sound proposition, as are optical control blinds designed to direct daylight deep into the room. Both systems make the lighting more attractive, heighten user comfort and improve the economy of the entire system.

6.5. Office Lighting

The right quality of lighting and visual design of the working environment is fundamental requirements for the efficient, fatigue-free performance of visual tasks. They also make for a sense of well-being and boost motivation. Quality of lighting is defined by a number of quality features. These must not be considered in isolation, however, because most of them interact with one another. Where no attention is paid to glare limitation, for example, a high lighting level can cause visual discomfort and give rise to annoying reflections on VDU screens. But lighting quality features are not the only factors that need to be considered. Visual comfort and the visual ambient of a room depend on an adequate supply of daylight, the design and colour scheme of the interior and daylight-dependent control of the quantity (lighting level) and quality (light colour, uniformity) of the lighting. (Figure 6-6)
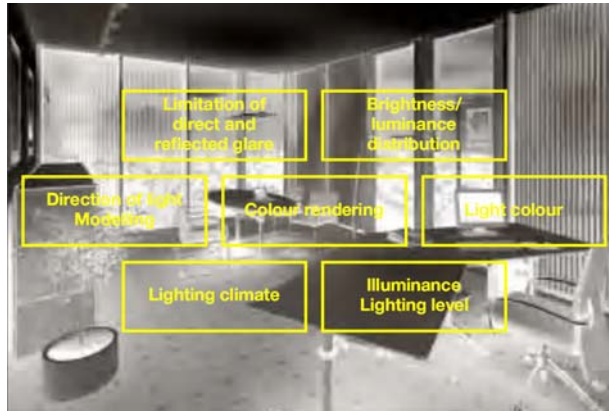
Figure 6-6 The quality features of lighting
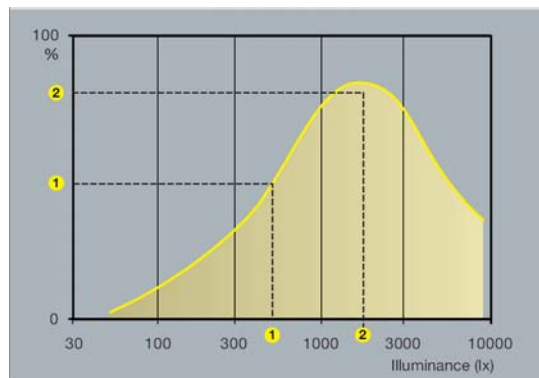
Figure 6-7 Subjective appraisal of what constitutes a "good" lighting level for reading at an office workplace: 1) Half of respondents happy with illuminance values of 500 lx or more, 2) A majority prefer illuminance values between 1000 and 3000 lx.

Fault-free, and fatigue-free performance of a visual task is crucially dependent on lighting level, which in turn is defined by illuminance (expressed in lux/lx). The higher the lighting level, the better the visual performance, i.e. the faster and more accurately we register visual information. The kind of illuminance levels found outdoors – where values range from 10,000 lux on a cloudy day to over 100,000 lux in bright sunshine – cannot be realized in a room. Studies show, however, that around 50% of respondents reckon that 500 lx illuminance is a good lighting level for reading. Having said that, the other 50% find it too low. (Figure 6-7) For accurate identification of faces and other vertical surfaces and objects in a room, the relevant yardstick is cylindrical illuminance (Figure 6-8).
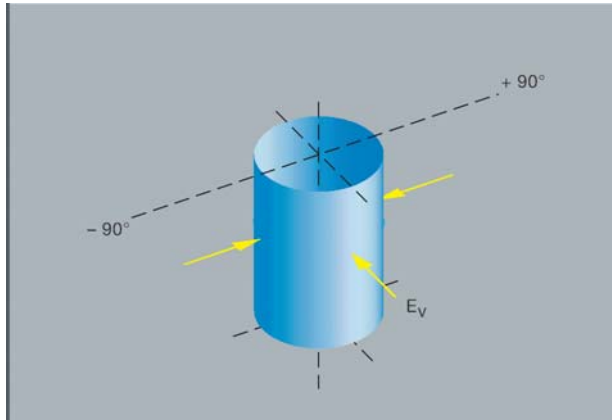
Figure 6-8 Cylindrical illuminance is the mean vertical illuminance on the surface of a cylinder

In an office, the lighting level needs to allow us to read and make out information on both screen and paper without difficulty. It must also permit visual communication with people around us and the working environment and help promote a general sense of well-being, motivation and dynamism. This calls for a balanced distribution of brightness in the visual field, i.e. the surroundings of the actual visual task. Brightness distribution depends on the uniformity of illuminance –primarily on the vertical surfaces of walls, cabinets and partitions – as well as the reflectance of such surfaces and the brightness (luminance) of windows. Recommended reflectance in offices: ceiling 0.7 to 0.9 walls 0.5 to 0.8 floor 0.2 to 0.4 work surfaces, furniture, equipment 0.2 to 0.7 the illuminance values recommended for various visual tasks are shown in the table on pages 36/37. The values stated are the minimum physiological requirements for a measure of visual satisfaction. Higher values are frequently preferred, however, especially by older people, because the average 60-year old needs around "twice as much light" as a 20-year-old. Higher values are also found useful during the darker months of the year, when they help maintain concentration and motivation. Illuminance must never fall below the recommended values. These are service values, designed to take account of the fact that with increasing length of service, illuminance decreases as lamps and luminaires age and become soiled and the reflectance of surfaces in the room declines. (Figure 6-9)
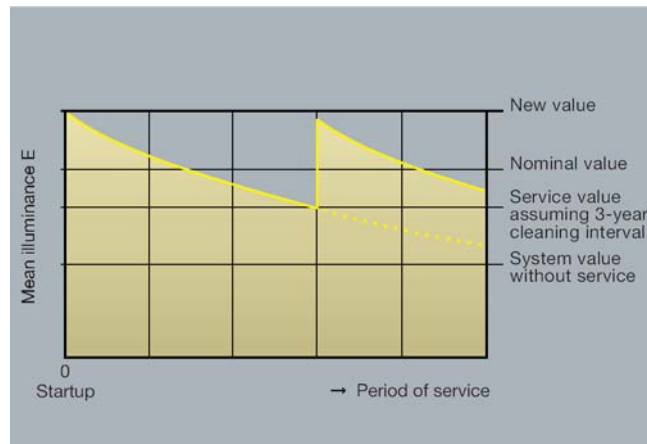
Figure 6-9 New value, nominal value and service value are local mean values at different points in a lighting system's life

To compensate for this decrease, new lighting systems need to be designed for higher illuminance (new value). The decrease is then taken into consideration in planning by the application of a service factor: service factor x new value = service value. The service factor depends on the types of lamps and luminaires used, exposure to dust and soiling in the room, service method and service intervals. In most cases, not enough is known at the lighting design stage about the factors that will define the rate of decrease in illuminance, so a service factor of 0.67 is applied for clean room conditions and 0.50 for dirty room conditions (e.g. rooms for smokers), assuming a three-year service interval and the use of modern lamps, electrical components and luminaires. The illuminance values recommended apply to the task area in which the visual task is performed. The task area can be a horizontal (e.g. table), a vertical (e.g. map) or an inclined surface (e.g. drawing table). Task areas typically found in an office are desks, conference tables/ areas, the vertical surfaces of cabinets and shelving systems, and stations for office machinery such as copiers and fax machines. (Figure 6-10,Figure 6-11).
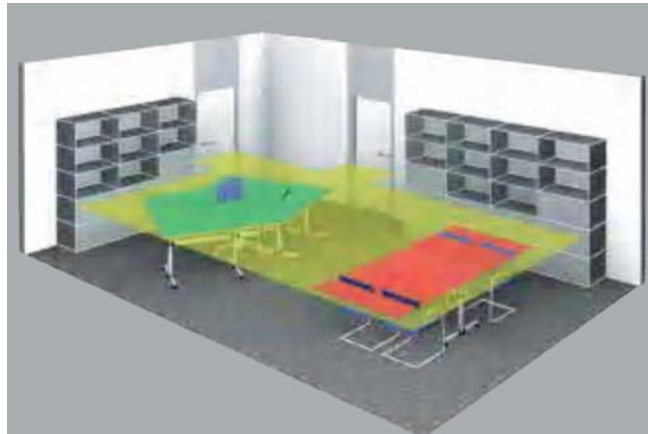
Figure 6-10 Horizontal task areas in an office: "VDU work" (green), "conference" (red) and "surrounding area" (yellow). Illuminance value reference height: 0.75 m above floor level

Figure 6-11 Vertical task areas in an office: e.g. "cabinet and shelving system surfaces" (blue) Illuminance value reference height: starting at 0.5 m rising to 2 m above floor level, width according to objects

DIN 4543 defines a "desk" task area as a work surface (desktop) plus a user area, the two together measuring at least 1600 mm x 1800 mm (Figure 6-12). Cabinet and shelving system task areas extend from 0.5 m to 2.0 m above floor level. Outside these task areas, a lower lighting level is permitted because the surrounding space is not used for the performance of demanding visual tasks.

Figure 6-13 shows the illuminance values required for task and surrounding areas and the minimum uniformity of illuminance expressed as the quotient of minimum and mean values.

Figure 6-12 Areas defined by DIN 4543: The VDU task area (green) consists of a work surface (white desktop) and a user area (red).

Task area	Surrounding area
750 lx	500 lx
500 lx	300 lx
300 lx	200 lx
up to 200 lx	up to 200 lx
E_{min}/E_m min. 0.7	E_{min}/E_m m in. 0.5

Figure 6-13 Illuminance values required for task and surrounding areas

Glare is one of the most discomforting of all visual problems. An unshielded general-diffuse lamp or the bright reflection of a window on a VDU screen places considerable strain on our eyes. Glare can have physiological consequences, e.g. impairment of visual acuity. A bright reflection on a screen can obscure information and render it indecipherable. In most cases, glare has at least a psychological impact, causing fatigue and loss of concentration. Visual performance suffers and we make mistakes. A distinction is made between direct glare and reflected glare. Direct glare occurs where a very bright point of light, e.g. the lamp of a luminaire, is located in the visual field. Direct glare can be avoided by the use of appropriate luminaires and correct positioning of luminaires and workplaces. Reflected glare occurs as a result of disturbing reflections on shiny or reflective surfaces. These surfaces can be VDU screens, items of furniture or glossy paper. So to avoid reflected glare, it is necessary to look at not only the type and arrangement of luminaires in the room but also the materials

and finishes of the office furniture and the positioning of monitors. Direct glare from luminaires in the past was appraised by the luminance limiting curve method described in DIN 5035. (Figure 6-14)
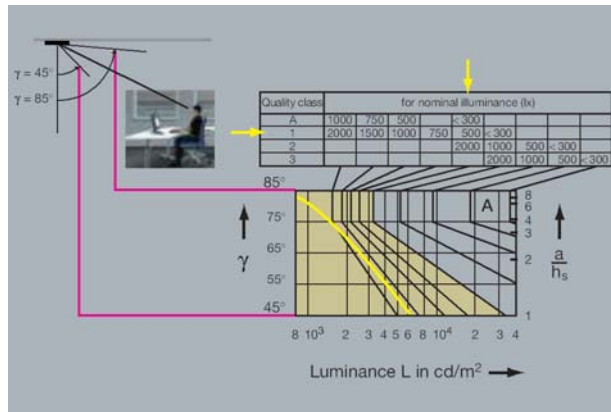
Figure 6-14 The currently used luminance limiting curve method defined in DIN 5035 assesses the mean luminance of luminaires in a zone of radiation from 45° to 85°. The new European standard sets UGR = 19 as a maximum permissible value for offices, which is equivalent to the luminance limiting curve for 500 lx in Quality Class 1.

Under the new European standard for interior workplace lighting DIN EN 12464, (psychological) glare is assessed by the unified glare rating method (UGR), which is based on a formula for glare. It takes account of all the luminaires in a system contributing to the sensation of glare. Glare is then rated by reference to the formula based UGR tables provided by lighting manufacturers. (Figure 6-15)

Figure 6-15 The UGR method takes account of all the luminaires in the system which contribute to the glare sensation as well as the brightness of walls and ceilings. It produces a UGR index.

The two methods – the one set out in DIN 5035 and the one defined in DIN EN 12464 – produce comparable results. Reflected glare on shiny horizontal surfaces (reading matter and paper for writing) is assessed by using the contrast rendering factor (CRF), which can be calculated by special software. For normal office work, a mean value of CRF = 0.7 is high enough; only work involving high-gloss materials calls for a higher value. (Figure 6-16)

Grade	Mean values	Minimum value	Application example
1	over 1,0	0,95	Work involving predominantly glossy materials, e.g. in graphic design offices
2	0,85 to 1,0	0,70	Work where glossy materials are occasionally used, e.g. in offices and schools
3	0,70 to 0,85	0,50	Tasks involving predominantly matt materials

Contrast rendering factors CRF and workplace requirements

Figure 6-16 Recommended CRF values for different materials used in office work
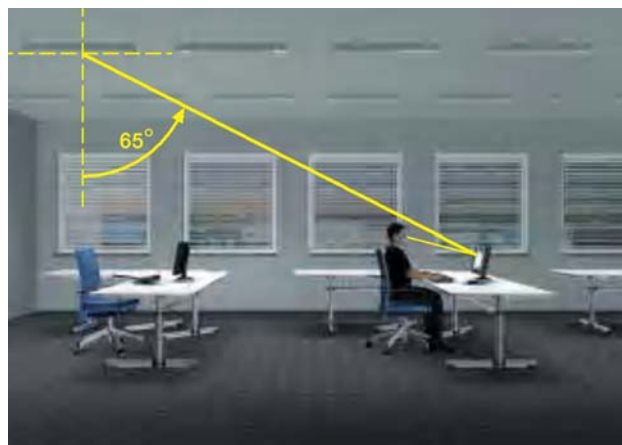
Figure 6-17 Depending on the class of VDU, the mean luminance of luminaires which could be reflected on the screen needs to be limited to 200 cd/m2 or 1000 cd/m2 above a threshold angle of radiation of γ≥65° (calculated at 15° intervals all around the vertical axis) to avoid disturbing reflections.

VDUs	mean luminance of luminaires and surfaces which reflect on screens
Positive display VDUs	≤ 1000 cd/m2
Negative display VDUs with high-grade anti-reflective system Evidence of test certificate required	
Negative display VDUs with lower-grade anti-reflective system	≤ 200 cd/m2

Figure 6-18 Classification of VDUs on the basis of anti-reflective systems and type of display. The cd/m2 values indicate the maximum permissible mean luminance of luminaires which could be reflected on the screen (in accordance with DIN EN 12464)

Reflected glare on VDU screens is the most common cause of complaints. It is effectively avoided where monitors are arranged in such a way that bright surfaces such as windows, luminaires and bright walls cannot be reflected on screens. Where such an arrangement is not possible, the luminance of the surfaces reflected on screens needs to be reduced. For luminaires, DIN EN 12464 sets out luminance limits (Figure 6-13), which depend on the type and anti-glare design of the computer screen used and apply to all emission angles over 65° to the vertical all around the vertical axis. (Figure 6-17) A positive (negative) display shows dark (light) characters on a light (dark) background. For a person to be able to register screen information without disturbance, VDUs with a lower-grade anti-reflective system require a greater reduction in luminaire luminance than high-grade anti-reflective screens. The table shows the maximum permissible mean luminance of luminaires which could be reflected on a screen (in accordance with DIN EN 12464). (Figure 6-18) Without light, we cannot see three-dimensional objects. Without shadows, we see them only as two-dimensional images. The parameters that define the depth and body of an object are direction of light and modelling – because light and shadow play a vital role in enabling us to make out shapes, surfaces and structures. A bright room with only diffuse non-modelling light makes a monotonous impression; the lack of visual guidance and the difficulty in identifying objects and gauging distances cause discomfort. Direction of light and modelling help define visual ambience. A good ratio of diffuse light – e.g. from indirect lighting components – to directional light –

e.g. from louvered luminaires or downlights – produces agreeable shadowing. The direction of light is generally determined by the daylight entering the room from a particular direction through the windows. Artificial lighting is used to prevent the excessive modelling that can result, for example, in disturbing shadows being cast ahead of our hand as we write. Where luminaires are arranged parallel to a window wall, the rear row of luminaires can lighten any dark shadows that might occur during the day. As daylight fades, the front row of luminaires near the windows can be partially or fully activated to replace the natural lighting. The light colour of a lamp is described in terms of the colour temperature T_f and units Kelvin (K). The Kelvin temperature scale begins at absolute zero (0 Kelvin ≈ –273 °C) The colour temperature of a light source is defined by comparison with the colour of a "black-body radiator". A "black-body radiator" is an "idealised" solid body – e.g. made of platinum – which absorbs all light hitting it and´therefore has a reflective radiance of zero. When a "black body" is heated´slowly, it passes through gradations of colour from dark red, red, orange, yellow´and white to blue light. The higher the temperature, the whiter the colour. The temperature in K of a "black body radiator" at which it has the same colour as the light source being measured is the most similar colour temperature of that light source. Lamps with the same light colour can emit light of completely different spectral composition and therefore quite different colour rendering properties. It is not possible to draw conclusions about the quality of colour rendering from the light colour.

The light colour of lamps:

Colour	Light colour temperature in Kelvin
warm white	<3300
neutral white	3300 – 5000
daylight white	> 5000

Colours have a significant bearing on the way we experience our surroundings. Whether a room has a warm or cold atmosphere is determined by the materials in it and their colours. The way the colours of objects are perceived, however, depends also on the colour rendering properties of the lighting. The colour rendering index Ra indicates how well colours are rendered by lamps. Where lamps have a high index of 90 or more, all colours are rendered very accurately; where the index is lower, the colours we perceive are corrupted. Reds then look

orange, greens appear yellow. Lamps are divided for convenience into colour rendering categories. Most lamps have a colour rendering index of over 80 and thus render colours well enough for us to perceive them as natural. Incandescent lamps, tungstenhalogen lamps, certain metal halide lamps and a number of fluorescent lamps have a colour rendering index of over 90, which means they render all colours very accurately.

7.	**Quality lighting assessment**

7.1. THE IMPORTANCE OF LIGHTING IN THE OFFICE ENVIRONMENT

Offices are designed to house working people engaged in thought and in a number of forms of communication (written, visual, telephone, computer, and face to face). Office lighting should enable workers to perform these tasks effectively. Since feelings of well-being, interest, and enthusiasm are affected by the environment, consideration should be given to the design of office interiors in an effort to achieve a stimulating work place. Office lighting affects the appearance of the space and its occupants, and therefore their mood and productivity. Naturally, lighting should provide good visibility for the visual tasks. Although it is important to consider the luminous environment and the lighting of visual tasks separately, these aspects must work together. The same lighting system may contribute to both, but typically, separate luminaires should provide or augment the visual task illumination. Energy-efficient lighting is critical to office lighting design. Good lighting design and applications go hand in hand with energy-efficient technologies to reduce operating costs and environmental pollution.

7.2. THE LUMINOUS ENVIRONMENT

The visual effect of an office space depends on variations in perceived brightness and color. The effects can be achieved by varying surface reflectances and illuminance. Shadow and light are both design elements. One example is wall washing, whereby the wall has a greater luminance than the ceiling or floor. Another example is local task lighting, which provides pools of higher brightness within a large space. This latter approach helps give office workers a sense of place at a workstation within an otherwise uniform open office. Careful design provides interesting variations without producing distracting or uncomfortable luminance differences.

7.2.1.   Color

Both surface reflectances and light source spectral power distribution (SPD) play important roles in the color of the office lighting environment. Color adds visual interest to a space, making it a more inviting and pleasant place to work. High color rendering by the light source is critical if fine color discriminations are being performed. The spectral composition of the light source can also determine the general overall appearance of a space, particularly the furnishings, room surfaces, and people in that space, and so should be considered when selecting a light source.

7.2.2.   Surface Reflectances.

Some believe that, where workers are exposed to the same environment for long periods of time, the color in that environment can affect performance positively or negatively, even if workers are not aware of this effect. Some also believe that small offices can be made to appear larger and less crowded if woodwork and furniture placed against walls have the same hue or a similar reflectance. Touches of accent color give vitality and dramatic interest to any office area. Contrasting colors, or light and dark values of the same color, can be used at some point or points in the room. These may be in wall coverings, furniture upholstery, or pictures or tapestries. Colors selected for large surface areas should have reflectances as recommended in Figure 7-1. Color contrast, through the use of more colorful surfaces, may also make interior spaces appear brighter at low light levels.
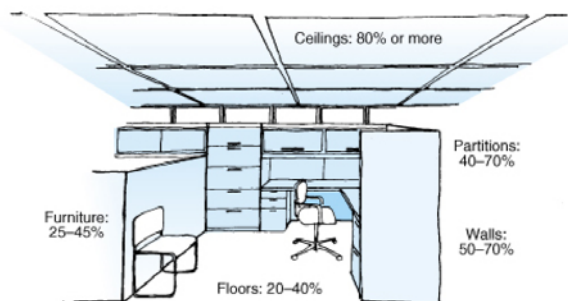
Figure 7-1 Reflectances recommended for room and furniture surfaces in offices.

7.2.3. Light Source Spectral Power Distribution (SPD).

There are two distinct application considerations with respect to light source SPD. These are the chromaticity (correlated color temperature, or CCT) and the color rendering properties of the light source. Chromaticity refers to the color appearance of the lighted source and is designated by its CCT in Kelvin (K). In interior spaces such as offices, a source will create a "warm" environment if its CCT is about 3000 K or lower, and a "cool" environment if it is 5000 K or higher. A CCT between these two is considered neutral. Individual preferences vary in regard to warm, neutral, or cool environments. The perceived color of an object is affected by the color rendering properties of the lamp. The color rendering index (CRI) is a measure of the color shift induced by a given lamp relative to a standard lamp of the same CCT. The maximum CRI value is 100. Where color discrimination is an important part of the work (for example, color matching in an advertising agency), a source with a CRI of 90 or higher should be employed. Two lamps with the same chromaticity may have different color rendering characteristics. Fluorescent lamps that are now available offer the designer several chromaticities with good to excellent color rendering and high luminous efficacy. The color rendering properties of various lamps can be demonstrated by installing them in display boxes or rooms, each having an identical presentation of colored objects. Light source selection depends on the importance given to color rendering, initial cost, lamping and maintenance costs, and energy costs. Because different sources render colors differently, it is important that the sources be viewed in a similar space before being specified. If daylight is present in the office, the colored objects should be viewed under the electric light source with and without the expected daylight contribution (taking into account possible tinting of the fenestration).

7.2.4. Color, Luminance, and Brightness Differences

Luminous differences and color contrast are necessary for vision. Achromatic print can be seen because of the difference in luminance between the white page and black print. Similarly, an interior space is visible because of the brightness differences of the surfaces. Brightness variations are a function of the absolute and spectral reflectances of the surfaces and of the distribution of light on those surfaces. Large brightness variations can be problematic. Office interiors should be lighted to provide for good visibility with no distracting glare. Direct and

reflected glare should be avoided; however, it is important to provide enough variation in luminance or color to contribute to a stimulating, attractive environment. Where there are no prolonged visual tasks, such as in lobbies and corridors and in reception, conference, lounge, and dining areas, variations in brightness are encouraged, using attractive colors and appropriate focal points of high illuminances to catch the eye. For an office environment, luminances near each task and in other parts of the office interior within the field of view should be balanced with the task luminance. Two separate phenomena are influenced by the luminance ratios within the field of view: dark and light adaptation and disability glare. To limit the effects of these phenomena, the luminance ratios generally should not exceed the following:

- Between paper task and adjacent VCT screen 3:1 or 1:3

- Between task and adjacent dark surroundings 3:1 or 1: 3

- Between task and remote (nonadjacent) surfaces 10:1 or 1:10

However, it is not practical or aesthetically desirable to maintain these ratios throughout the entire environment. For visual interest and distant eye focus (for periodic eye muscle relaxation throughout the day), small visual areas that exceed the luminance-ratio recommendations are desirable. This would include artwork, accent finishes on walls, ceilings or floors, small window areas, accent finishes on chairs and accessories, and accent focal lighting. The visual system adjusts its operating characteristics as a result of changes in the brightnesses within the field of view. Photochemical, neurological, and pupillary changes occur in this adaptation process. Neural changes occur most quickly, although visual capabilities are temporarily impaired while the visual system readjusts. This is known as transient adaptation, which is completed after a very short time (less than 200 ms). Photochemical changes occur much more slowly and are most noticeable when there is a dramatic change in ambient light level, such as moving from full daylight into a dark theater. Pupillary changes are relatively insignificant in the adaptation process.

7.2.5.   **Disability Glare.**

Glare sources within the field of view may cause stray light within the ocular media of the eye. This light is in turn superimposed on the retinal image. This reduces the contrast of the image and can reduce visibility and performance.

7.2.6.   Reflectances and Finishes.

The brightnesses of objects depend on illuminance as well as surface reflectance. For example, reading 80%-reflectance white paper on an evenly illuminated desk top requires that the desk top have a reflectance of at least 27% (one-third of 80%) in order to comply with the 3:1 guideline for the ratio between the luminance of the task and its immediate surroundings. Dark wood or veneer work surfaces often have lower reflectance values and exceed the recommended value. Thus, reflectance as well as illuminance levels are important in office lighting design. Surface specularity, or gloss, must also be considered. Glossy surfaces are mirror like and can produce images of the luminaires that can result in reflected glare, a patch of very high brightness. Glossy horizontal work surfaces are particularly troublesome (Figure 7-2). For this reason, shiny work surfaces should be avoided.
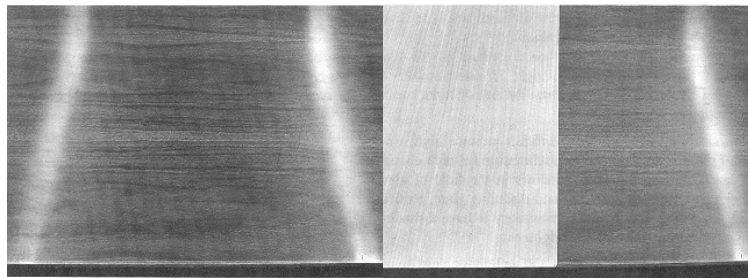
Figure 7-2. The streaks of light are reflected images of two continuous rows of luminaires. A very severe glare condition is produced by a desk top that is both dark and specular. The reflected glare disappears when a piece of light matte material is placed over the dark specular top.

If shiny horizontal surfaces cannot be avoided, a relatively low-brightness, indirect lighting system can be used to provide ambient illuminance. It is important that the luminaires have a broad light distribution pattern to provide essentially even ceiling luminance. The ratio of 5:1 or better between the darkest area between luminaires and the brightest area directly above the luminaire can be considered even ceiling luminance. If the maximum ceiling luminance is less than 425 cd/m^2, the potential for harmful reflections is very low. Local task lighting located on one or both sides of the task can be used to supplement the ambient illuminance. By placing task lighting luminaires to the sides of the work area, reflected glare from a shiny desk top is eliminated at the worker's viewing position. In private offices, if the furniture location is known, direct ceiling-

mounted luminaires can be located so that, again, specular reflections from the luminaires off the desk top are minimized for the worker.

7.2.7. Visual Comfort

Discomfort glare is a sensation of annoyance produced by brightnesses in the visual field that are significantly higher than the brightnesses of the surrounding areas. The magnitude of the sensation depends on the size, position, relative brightness, and number of sources in the field of view. A comparison of glare control from various luminaires can be made from photometric reports by comparing the average luminance values produced at 0° (vertical), 45°, 55°, 65°, 75°, and 85° in the lengthwise, crosswise, and (sometimes) diagonal planes.

Discomfort glare becomes less important as the light source is farther from the line of sight. However, sources of intense brightness, even well above the line of sight, can be distracting or unpleasant.

7.2.7.1   *Fenestration*

Windows and skylights produce high, variable brightnesses. Frequently brightnesses are high enough to cause glare, particularly windows in the field of view. They can also cause reflected and disability glare, particularly for VDTs. It is therefore necessary to have a shading device to control the window brightness.

7.2.7.2   *Electric Lighting and Daylight.*

Office lighting must be adequate for work after dusk. During the day, with proper controls, daylight can replace some electric lighting. One way of integrating daylight with electric light is to circuit perimeter luminaires on a separate circuit that can be manually or photoelectrically switched or dimmed. Horizontal blinds or refractors can control brightness and, to some extent, redirect light in useful directions.

7.2.8. The Importance of Visual Tasks in Offices

Office work entails a variety of visual tasks. In addition to creating a pleasant and stimulating environment, office lighting should support the various visual tasks performed. The visibility of task details is determined by their size and contrast with the background, the absolute luminance of the background, and the viewing duration. Although visual performance follows a law of diminishing returns, one

can say that in general the greater the contrast and size of the task details, the higher the background luminance, the longer the viewing duration, and the higher the level of visual performance. Within limits, a given level of visual performance can be maintained by trading off reductions in the magnitude of one factor with improvements in another. So, for example, leaning forward to make task details appear larger can offset reduced background luminance caused by low illuminances. Visibility also depends on the age of the worker. As a person ages, the pupil becomes progressively smaller (for a fixed level of ambient illumination) and the crystalline lens becomes thicker and less transparent. For example, a typical 50-year-old needs twice the illuminance falling on a task that a typical 20-year-old needs for that task to provide the same amount of light falling on the retina.

7.2.9.   Illuminance Selection

Illuminance levels should be determined based on visual performance research as well as on design experience. The procedure is task specific, and knowledge of the task is important. If a specific task is unknown, then the designer must design for typical office tasks. If possible, a survey of future occupants should be conducted to gather information about the activities that will occur in the space and the ages of the people who will perform them. The designer can tailor the illuminance to the specific situation. The designer is provided with this flexibility in order to specify a level that is suited to the visual task, keeping in mind the lighting design issues. In determining an appropriate illuminance level, the designer must also consider how the illuminance is to be delivered, and to what locations. It is essential to differentiate between general lighting for the space and the illuminance specifically on the task or at the task location. In open plan offices, providing task level illumination only at specific task locations and at a lower illuminance level throughout the space is typically appropriate. In private offices with free standing desks, it is more likely that the general illumination of the room provides the task level illumination. The general illumination level of an office facility should be determined by several factors. The reflectance values of surfaces surrounding the task area should be considered to create a visually comfortable environment. Luminance levels surrounding the task should not be greater than three times the luminance value of the task, or less than one-third the luminance value of the task. If the offices contain VDTs, the general

illumination should meet the guidelines established for that specific type of task. Additionally, the general illumination should meet the psychological need for light of the occupants of the space. It should be remembered that room reflectance values and the distribution characteristics of the luminaire may be as important as illuminance level.
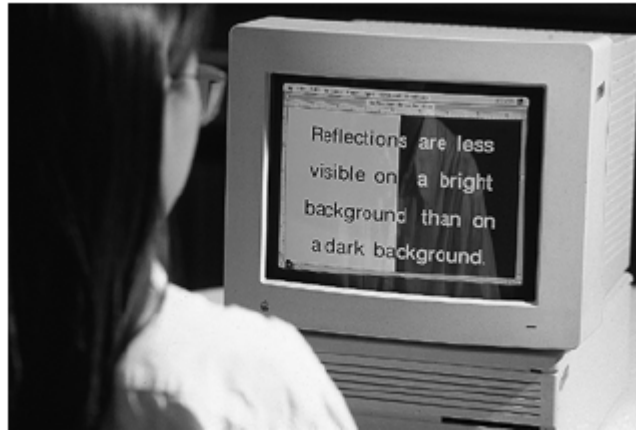
Figure 7-3 In a VDT screen, veiling reflections from bright objects, which reduce contrast, are prominent on a white-on-black display (right side of screen). These reflections are less noticeable on a black-on-white display (left side of screen).

If there is more than one task in the space, with each requiring a different illuminance, the designer must choose among them. There are several alternative methods for combining different target values. The illumination requirements of different tasks may be satisfied by providing different task lights. A flexible lighting system, individual dimming controls, and multilevel switching are other available alternatives, depending on furniture layout and architecture. For locations with multiple tasks, designers can design for the task requiring the highest level of illumination and provide dimming capabilities that allow the user to adjust the lighting level in various areas to suit different tasks. Multilevel lighting systems also may be appropriate. If flexibility is not possible, the designer may be forced to choose one criterion over another for the entire system. However, it should be noted that most task lights provide more than enough illuminance. Often, office buildings are built on speculation, so that the visual tasks and the occupants are unknown. A building in which the lighting has been thoughtfully designed for today's typical office tasks is more attractive for prospective tenants. A logical recourse is to design for the modern electronic office in which a combination of paper and VDT tasks will be performed. Ambient

illuminances throughout the office space should not exceed 500 lx, where VDTs are used, and extreme care should be given to providing a general lighting system that does not create disability glare, or reflected glare off of VDT screens. Higher illuminances at task locations can be provided by task-light luminaires.

Quality of Lighting

It should be remembered that task visibility can be affected by the quality of light. Poor lighting quality can provide veiling reflections, reflected glare, and shadows, resulting in reduced visibility. The angle at which light strikes the task, the location of the luminaires relative to the task, the distribution of the light emitted from the luminaires, the location of luminaires in the office, and the specific properties of the task and work surface all affect lighting quality. The contrast of a visual task depends on the glossiness of the task surface and on the geometric relationships between the light sources, the task, and the eyes. If the visual task produces a mirror angle between the eye and the luminaire or another bright object, contrast is reduced. This effect is called veiling reflections. The area from which a luminaire or bright object can reflect light off the task and into the viewer's eyes is termed the offending zone. This may be a specific area of the ceiling or, often in open-plan workstations, the area directly in front and above the occupant, which is a common area for placement of task-light luminaires (Figure 7-4). Like ceiling luminaires, task lighting, either as desk luminaires or as part of open-plan furniture systems, ordinarily should not be placed in the offending zone. However, the light distribution characteristics of some luminaires minimize veiling reflections through optical design elements. Such luminaires may be placed in the offending zone if they use an optical system that redirects light so that these veiling reflections are eliminated or at least reduced. This can be accomplished with lenses and/or reflectors. Many task lights use a batwing lens. This type of lens is made up of a series of linear prisms that minimize the light output at nadir (straight ahead) and redirect light out to the sides. As a result most of the light striking the task originates from the sides or ends of the task light (Figure 7-5). Free-standing or mobile-arm task lights allow the user to position the light for best task visibility (Figure 7-6). This may be a useful approach when linear task lights cannot be used. Many of these portable task lights offer little optical control; a shade can block light from the user's eyes, and generally most of the light is concentrated directly below the unit.
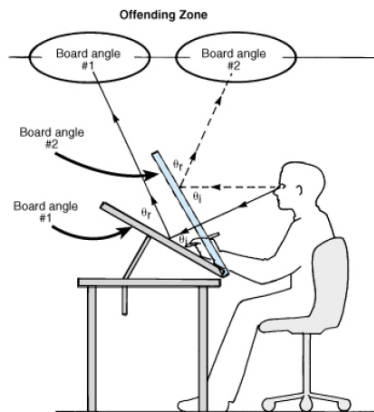
Figure 7-4. The offending zone moves with board angle changes and with eye movements relative to the task surface.
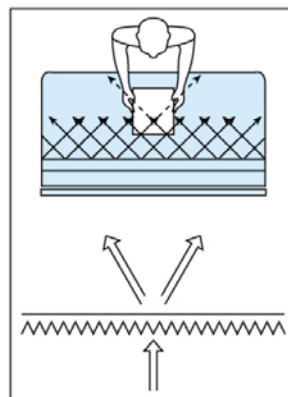
Figure 7-5. Task light with a batwing lens that directs light out to the sides.
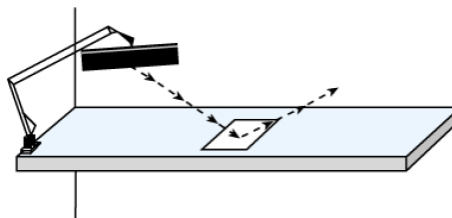
Figure 7-6. Portable task light. Arrows indicate the mirror angle.

The designer should always consider multiple working areas within the space. In open office areas, for example, one luminaire placed outside the offending zone

for one worker may be in the offending zone for another. Luminaire light output should be limited at angles greater than 55° from vertical in order to prevent veiling reflections and to reduce discomfort glare.

Reflected glare is usually caused by a mirror image of the light source in the offending zone reflected to the worker's eyes from VDTs or highly polished wood or glass-covered desk tops. It can be reduced by the use of matte surfaces and by carrying out the procedures for reducing veiling reflections on the task. Additionally, large-area low-luminance luminaires or indirect luminaires can be used when specular surfaces cannot be avoided.

In most office work, shadows reduce visibility. Shadows reduce the illuminance on the task and, if sharply defined, can be distracting and cause excessively high luminance ratios on desk tops. Shadows are minimized if the light arrives at the task from many directions, helped by high-reflectance matte finishes on room surfaces. Large area luminaires can also reduce shadows.

Workplaces that have dark walls and ceilings may not be as well accepted by employees as spaces with bright room surfaces. White and light-colored paint finishes, combined with the washing of walls and ceilings with light, can brighten both the space and worker attitudes. This applies to furniture, too. Dark brown partitions and walnut grain work surfaces may not look as cheerful as lighter finishes, and they certainly do not use lighting energy as efficiently. Gradients of light on a wall, ceiling, or desk top affect brightness perceptions. Until there is a better understanding of this, it is a good idea to avoid harsh or striated patterns of luminance. Even more important, patterns of light must make sense; otherwise they are distracting. A scallop of light on a wall looks odd, for example, unless there is a piece of art centered in it or it is one of several rhythmical scallops that correspond to the spacing of wall panels. In spaces such as conference rooms, interview rooms, and video conference facilities, faces should be easily seen and pleasantly lighted. Strongly directional downlighting, for example, can cause harsh raccoon-like shadow patterns on the face. Diffuse lighting or light bounced off of surfaces can help soften shadows and make facial features more readable.

People's preferences for warm or cool light sources are often cultural or climate related, so it is difficult to recommend color temperatures appropriate for office spaces. However, the color rendering ability of the lamp is important if food,

faces, or fine architectural finishes are involved. In general, choose lamps of 70 CRI or greater, or 85 CRI or above if color critical tasks are being performed.

Perceived flicker can cause headaches. Electronic ballasts can eliminate flicker for fluorescent lamps, and magnetically ballasted HID lamps can be wired to alternate phases of a three-phase system to reduce flicker.

Access to windows provides many benefits for workers. It provides a view, allowing an individual to relax his or her eyes by focusing on distant objects. It provides a contact with time of day, weather conditions, and activities outdoors. If designed to introduce daylight without glare, windows and skylights can provide ambient light, reducing the need for electric light during daylight hours.

7.2.10.   THE PSYCHOLOGICAL EFFECT OF LIGHTING IN OFFICES

7.2.10.1   *Subjective Responses*

Although office spaces are primarily task oriented, other less quantifiable effects of lighting on user's satisfaction and well-being should also be considered during the lighting design process. There is a body of literature that discusses the subjective responses to lighting. Although this literature is not extensive, some guidelines can be suggested to the lighting designer. In general, the underlying belief is that light not only provides the physical stimulus necessary for visual performance, but also communicates or reinforces certain cues that influence people's subjective impressions of the environment surrounding them. These impressions can make a significant impact on long-term user satisfaction in the office. Four characteristics of lighting systems have been shown to be important in influencing subjective impressions. These characteristics are defined in general terms as overhead/peripheral, bright/dim, uniform/non-uniform, and visually warm/ visually cool. By varying the emphasis of the lighting system in each of these lighting modes, the designer can influence the types of impressions he or she believes are desirable for the particular project being developed. By doing so, the designer has the opportunity to enhance desirable characteristics of the office workplace (e.g., selecting a high color rendering light source to reinforce aspects of visual clarity), while helping to overcome its inadequacies (e.g., perimeter wall lighting to evoke impressions of spaciousness in a small office or conference room). Of course, people's impressions of architectural

interior environments are influenced by many factors in addition to lighting, such as room size and proportions, type of space, furnishings and finishes used, and furniture layout. In many cases, these other factors provide a stronger influence on some subjective responses than will the lighting. Variations in the intensity, distribution, and color tone of the lighting exert some influence, intentional or not, on subjective impressions such as spaciousness, relaxation, visual clarity, and pleasantness. These influences must be carefully considered as an integral part of the office lighting design process. Admittedly, these guidelines are qualitative in nature, and the actual psychological effects of a particular lighting design solution are difficult to predict with confidence. However, ongoing research is taking place o develop methods for better predicting these effects during the design process. Efforts to define quantitative aspects of the lighted environment or to develop computer graphic models of lighted spaces how potential in providing design tools that assist the designer in predicting the subjective effects of lighting.

7.2.11. Lighting Methods

7.2.11.1   *General Lighting versus Localized Lighting.*

There are basically two methods for lighting office tasks. One is to design the general lighting so that required illuminances are provided at all task locations. This is most appropriate for private offices or special situations where task lighting is inappropriate. The other is to supply localized lighting from task-lighting luminaires in conjunction with a low level of general illumination. In open-plan arrangements where vertical partitions or storage cabinets over work surfaces cause shadows, localized lighting becomes essential for adequate task illumination and shadow reduction (Figure 7-7). When localized lighting is used, the general illumination should be designed with a low illuminance appropriate for circulation, for casual viewing of tasks, and to provide the recommended luminance ratios between the task and other areas within the field of view. The design of the general illumination can also be better coordinated with the interior design and the architecture.

7.2.11.2   *Direct, Indirect, and Direct-Indirect Lighting.*

Alternatives for general lighting are direct (downward), indirect (upward), or a combination of the two (Figure 7-8). Indirect lighting illuminates the ceiling, which

in turn reflects light downwards. Thus, the ceiling becomes the brightest surface in the visual field (Figure 7-9). To avoid excessive luminance, the illumination on the ceiling should be evenly distributed. Two criteria that should be established in evaluating an indirect lighting approach are maximum ceiling brightness, typically directly above the luminaire, and uniformity ratios. The maximum allowable ceiling luminance should be determined by the task illuminance requirements. If the primary task in a large office space is reading a VDT screen, the maximum allowable ceiling luminance should not exceed 850 cd/m^2. The uniformity ratio is the ratio of the brightest area of the ceiling, typically above the luminaire, to the darkest area of the ceiling, between luminaires, in other words, the ratio of the maximum to the minimum. In a VDT-intensive environment, better uniformity results in less noticeable glare on the screen. Ratios up to 8:1 are acceptable with light background screens; however, 4:1 creates a lower potential for glare and should be the target maximum for dark background VDTs. 2:1 ratios are achievable and more desirable. The designer should attempt to provide as smooth a gradient as possible between the high and the low luminance. If the maximum ceiling luminance is less than 425 cd/m^2, this low luminance is not reflected in VDT screens, and thus ceiling luminance uniformity is not important.

Figure 7-7. A workstation with built-in task lighting illuminating the desk top below. The low brightness ceiling luminaire with parabolic louvers cuts down on reflections on the VDT screen.
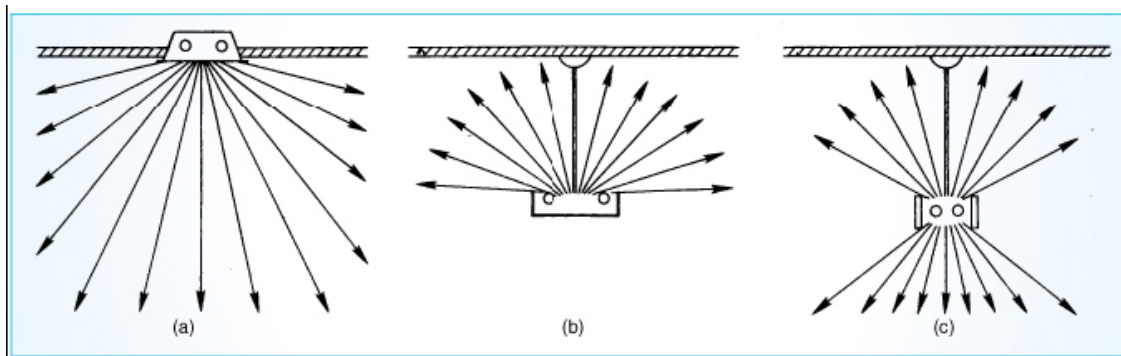
Figure 7-8. Luminaires for general lighting are classified in accordance with the percentage of total light output emitted above and below the horizontal. Three of the classifications are (a) direct lighting, (b) indirect lighting, and (c) direct-indirect lighting.

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Figure 7-9. Pendant luminaires are commonly used to provide indirect illumination.

If VDTs are not present, higher ceiling luminance may be allowed. The ratio (R) of the maximum average ceiling luminance to the luminance of the task should not exceed 10:1. For example, a 75% reflectance task (ρ = 0.75) illuminated to 500 lx (E) would limit the ceiling luminance to approximately 1200 cd/m2, according to the following equation:

$$L_{cmax} = \frac{\rho E R}{\pi}$$

$$L_{cmax} = \frac{0.75 \times 500 \times 10}{\pi} = 1194 \text{ cd/m}^2$$

Ceiling uniformity also should be assessed in terms of aesthetic considerations and of acceptable luminance ratios between the task and more remote surfaces. If extreme ceiling luminances are present, lower visual comfort can result. Many indirect luminaires emit light below the horizontal plane. This can provide both an increased sense of perceived brightness and a recognizable source of light.

If a luminaire does emit light below the horizontal plane, the average intensity in the lengthwise, crosswise, and 45° horizontal planes, at angles between 55° and 90° from vertical, should be limited to avoid direct glare. Indirect lighting can provide a calm, diffuse light that is void of highlights and shadows, similar to the

light of an overcast day. Indirect lighting can provide good visual task illumination, since it tends not to cause bright images in VDT screens nor appreciable veiling reflections on paper-based tasks. It may be especially good for drafting tasks because it does not create shadows from the tools used to perform the task. It may, however, reduce the sense of visual clarity, depth perception, or orientation. The lack of highlight and shadow minimizes visual cues. This problem can be addressed by using more color, adding accent lighting, or wall washing, all of which establish visual cues and make it easier to interpret the visual environment, as well as to contribute to the pleasantness of the space. A major consideration in designing an indirect lighting scheme is the selection of lamps. The most common choices are metal halide and fluorescent. These sources differ greatly as to luminaire size and color. Luminaire size varies because of the inherent difference in the lamp sizes and, as a result, the luminaire shape and scale can determine luminaire location and the appropriateness of the design. Color consistency is an important consideration when lighting a flat, white plane, such as the ceiling. The color shift in metal halide lamps through life is more noticeable when illuminating a ceiling plane than downlighting the floor.

Direct lighting emphasizes horizontal planes, such as work surfaces and the floor (Figure 7-10). Floor colors are reflected and may actually tint the ceiling. With wide-distribution luminaires and perimeter placement, direct luminaires emphasize vertical surfaces. There is a wide range of direct-type luminaires with a variety of distribution characteristics. These characteristics are dependent on lamp type, size, and reflector and shielding materials. Light distributions range from broad, using translucent diffusing shielding, to concentrated, using specular reflectors and louvers.

Figure 7-10 Direct lighting from a fluorescent system that provides good general illumination as well as adequate light for working at the drafting table.

Luminaire light distributions may be compared by reference to their intensity distribution curves and related values on a photometric report. Luminaire luminances can also be compared by referring to the luminance summary section of a photometric report. This information is typically given in two or three horizontal planes (lengthwise, crosswise, 45°) at angles of 0° (vertical), 45°, 55°, 65°, 75°, and 85°.

7.2.11.3 *Diffusers.*

A diffuser scatters the light emitted by the lamps before it leaves the luminaire. Since the area of the diffuser is much larger than the area of the lamps, the total flux is more evenly distributed, and thus the average luminance is less than that of bare lamps. Nevertheless, the average luminance of a diffuser is still rather high and nearly constant for all viewing angles. In a large office, diffusers may have low VCP as well as producing unacceptable reflections in VDT screens. Diffusers are not recommended for open office environments, except when a

special effect is desired, such as with a luminaire that mimics a skylight. In small private offices, they may be appropriate if they are not visible at viewing angles required for visual tasks. Their broad distribution does not create excessive brightness on the walls.

7.2.11.4   *Lenses.*

A lens incorporates a series of small prisms that reduce the apparent brightness of the luminaire at the near-horizontal viewing angles of 45° to 90° from vertical. Depending on the specific optical characteristics of a lens, acceptable glare ratings may be obtained. However, most lenses do not reduce glare sufficiently to prevent luminaire reflections in VDT screens. The luminaire efficiency depends on the specific lens.

7.2.11.5   *Polarizers.*

Polarized light can reduce veiling reflections and reflected glare under special conditions. Some commercially available luminaire lenses are designed to polarize the emitted illumination by transmitting light through multiple refractive layers. The degree of polarization in the illumination depends on the number of layers through which the light is transmitted, as well as the angle of transmission. There is no polarization produced at the angle perpendicular to the transmission plane, that is, directly below the luminaire. As the angle of transmission increases, for a given number of layers, the degree of polarization increases up to Brewster's angle, approximately 60° for these lenses. At this angle, and depending on the number of transmission layers, the light can be polarized by between 30 and 50%.

The benefits of polarized light in reducing veiling reflections and reflected glare depend on the degree of polarization in the illumination, the luminaire-task-eye geometry, and the specular characteristics of the task surface. Because the effectiveness of polarized light depends on all of these factors, it is difficult to provide a general statement on polarized light that is correct for every application. Guidance on the significance of polarized light for a specific application can be obtained from the literature. The luminances of luminaires using polarizing materials should also comply with VCP recommendations for typical offices, and the luminance guideline for spaces with VDTs.

Luminaires with a grid of parabolic louvers having a specular finish can control brightness precisely. The louver is an array of open cells, the walls of which form parabolic reflectors. The cells range in size from 12.5 cm × 12.5 cm (0.5 in. × 0.5 in.) to almost 30 cm × 30 cm (12 in. × 12 in.). The smaller cell types are usually injection-molded plastic, which is then vacuum metalized with aluminum. The larger cell types are usually fabricated from aluminum sheets, usually anodized prior to forming. When either type is made with a specular finish, the light output can be precisely controlled so that practically no light is emitted at angles above the cutoff angle. When this is the case, the louver can look darker than the ceiling. This precise light cutoff angle also darkens walls near the ceiling and places greater importance on illuminating vertical surfaces.

Parabolic louvers do not always have a sharp cutoff or a low luminance. Their optical performance depends on the degree of specularity of the louver surface and the optical cutoff of the louver. A semi-specular finish diffuses the light reflected from the louver surfaces and, at angles of view above the nominal cutoff angle, provides some luminance rather than the dark surface achieved with very specular surfaces. A semi-specular finish also tends to hide dust, fingerprints, and imperfections in the reflector surface. However, the semi-specular luminance may show up as a reflection on VDT screens. Aluminum finishes can provide a middle ground, as they often offer higher luminance then specular aluminum beyond the cutoff angle, but not as high as found with typical semi-specular material. Parabolic louvers actually have two cutoff angles. The first is the physical cutoff angle, which is the angle from vertical that just occludes a view of the lamp. The second is the optical cutoff, which is the angle from vertical at which light reflected from the parabolic surfaces is just occluded. This angle depends on the precise shape of the reflector surfaces and is not always the same as the physical cutoff angle. For a precise cutoff, the two cutoff angles should be the same (Figure 7-11).

The degree of specularity and the louver cutoff angles are not usually included in luminaire specifications. The shielding angle sometimes given in photometric reports refers to the angle from the horizontal at which a direct view of the bare lamp first becomes visible. However, the performance of a luminaire resulting from the degree of louver specularity and from the louver cutoff characteristics can be determined from the luminaire photometric report. The luminance

summary table in the report can be used to compare and select direct-lighting luminaires, especially for offices with VDTs. The luminance summary table shows the luminaire luminance at various angles measured from the vertical. The table typically shows these values in the lengthwise and crosswise horizontal planes. It is an advantage when the table also gives values for the 45° plane, as this may reveal a higher luminance at a given angle than for lengthwise and crosswise planes (Figure 7-12).

7.2.11.7   *Direct-Indirect Lighting.*

A combination of direct and indirect approaches can produce excellent results (Figure 7-13). Luminaires that provide both upward and downward light are most commonly used for this application. The indirect portion should have characteristics so as to not create hot spots or excessive luminance on the ceiling. The direct portion should provide diffuse lighting and adequate shielding to provide good visual comfort and avoid glare. The results of direct-indirect lighting can be quite satisfactory. Typically this design solution obscures the inadequacies of each individual approach and maximizes the advantages of each, creating both a pleasant and a functional environment.
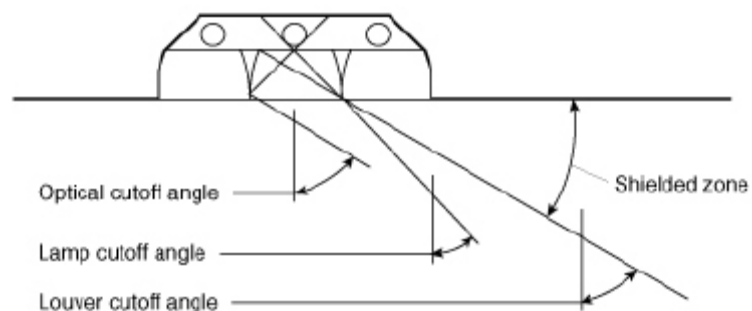
Figure 7-11. The blades of a parabolic louver provide a physical cutoff in the same way as an egg-crate louver; however, a parabolic louver with a specular finish reflects light from its curved blades at an angle equal to or less than the louver cutoff angle.

XYZ Photometric Laboratories
Certified Test Program
Computed by XYZ program

Report no.: ABC Company: 0000!
Prepared for ABC Company
Catalog no.: ABC00000
Luminaire: Fabricated metal housing, white painted reflector, specular parabolic louver
Lamps: Three F40T12/CW, each rated 3150 lumens
Ballasts: One X000, one CDE X000Z
Mounting: Recessed
Lumen to candela ratio used = 9.17
Total input watts = 131.1 at 120.0 volts
The 0-degree plane is parallel with the lamps

Candela Distribution

	0.0	22.5	45.0	67.5	90.0	Flux
0	2876	2876	2876	2876	2876	
5	2875	2887	2899	2919	2915	278
15	2739	2831	2982	3102	3122	844
25	2485	2700	3197	3703	3767	1462
35	2150	2532	3074	2939	2835	1706
45	1545	1987	1688	1302	1290	1208
55	24	108	295	159	120	214
65	0	0	0	0	0	0
75	0	0	0	0	0	0
85	0	0	0	0	0	0
90	0	0	0	0	0	

Zonal Lumen Summary

Zone	Lumens	% Lamp	% Fixt
0– 30	2584	27.3	45.2
0– 40	4290	45.4	75.1
0– 60	5711	60.4	100.0
0– 90	5711	60.4	100.0
90–180	0	0.0	0.0
0–180	5711	60.4	100.0

Total luminaire efficiency = 60.4%
Total reflectance of paint = 91.3%
CIE type = direct
Plane : 0-deg 90-deg
Spacing criteria : 1.2 1.4

Luminance data in candelas per square meter
Angle Average Average Average
0-deg
2700
310
0
0
0

Legend
0–deg: ....
45–deg: – – –
90–deg: ———
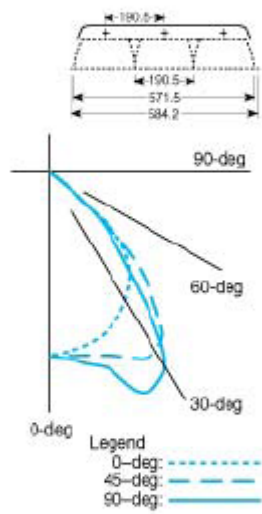
Luminance data in candelas per square meter

Angle in deg	Average 0-deg	Average 45-deg	Average 90-deg
45	3240	3535	2700
55	60	760	310
65	0	0	0
75	0	0	0
85	0	0	0

Figure 7-12. A typical photometric report showing the luminance summary table.

Figure 7-13 An open-plan office with direct-indirect fluorescent luminaires in a regular pattern, providing ambient light for the workstations beneath.

7.2.11.8   *Photometric Data.*

An intensity distribution curve, which is a part of the luminaire photometric report, will show how light exits the luminaire. This curve helps to determine luminaire placement, layout, uniformity, and whether or not the luminaire can achieve the desired results for both illuminance and luminance criteria.

Along with the intensity distribution, a photometric report can also provide information on luminaire luminance. The luminance summary data provide information on the average luminance of the luminaire at a variety of angles in several planes. Along with the luminance summary, VCP data give further information on luminaire brightness for direct luminaires within the context of a given set of spatial dimensions. It should be noted that most VCP data are reported for task illuminance of 1000 lux (100 fc). For lower-illuminance applications, additional VCP data should be requested. Within open-plan offices, where large ceiling areas are within typical fields of view, and especially in VDT-task environments, where the tasks are typically performed in a heads-up position, the VCP should be at or above 80. In smaller private offices, VCP data are less significant because of partitions, unless full-height walls are brightly illuminated and the ceiling luminaires are visible.

7.2.11.9   *Final Selection Process.*

Although much of a luminaire's performance can be evaluated through data analysis, the final selection process should include more than just reviewing printed information or photographs. Actual luminaire samples should be obtained and examined. Physical inspection of the luminaire can reveal aspects of both performance and quality not represented in printed information. A mock-up is a further step to assure the quality of both the design and the luminaire selection. Mock-ups should duplicate the characteristics of the final space as closely as possible. Variations in finishes or ceiling heights, for example, may greatly influence perceptions. Also, mock-ups should contain a suitable number of luminaires so that appropriate judgments can be made concerning illuminance values under realistic conditions. If a mock-up is not feasible, visits to installations with the same luminaires give both designer and client the opportunity to see the luminaires function, even if the spatial conditions are different.

7.3.   Lighting quality

Patterns of light and dark affect both our perceptions of the world and our emotional and physiological responses, and thus they are essential in gathering information about the physical world. Good-quality lighting can support visual performance and interpersonal communication and improve our feelings of well-being (Figure 7-14) Poor-quality lighting can be uncomfortable and confusing and can inhibit visual performance. This chapter defines and discusses lighting quality.
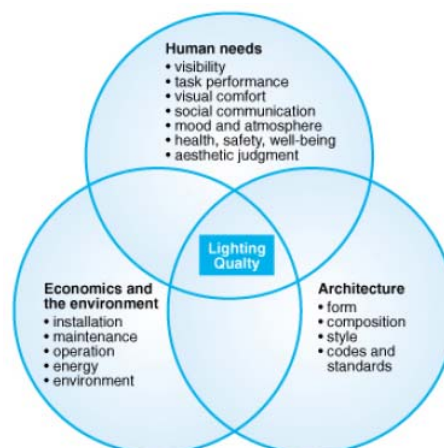
Figure 7-14 Lighting quality: integration of human needs, architecture and Economics and the environment.

The overall purpose of lighting is to serve the needs of people. The role of the lighting designer is to match and rank the needs of the people using the space with the economic and environmental considerations and the architectural objectives, and then to translate the results into a workable design and functional installation. The human needs served by lighting are identified in Figure 7-15.
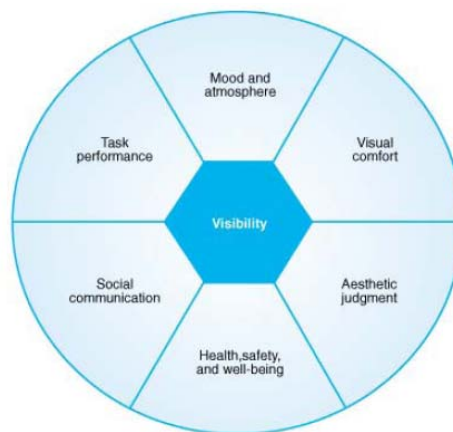
Figure 7-15 Human needs served by lighting.

7.4. Lighting for Human Needs

The needs of people are complex. Emotions, actions, perceptions, and health are influenced by lighting. Central to human needs is visibility, because it is the detection and organization of light patterns that allow a person to analyze and evaluate the environment. Once objects and patterns are visible, one can use a pencil to write a note, learn to pronounce new words by following the facial expressions of a teacher, walk down a corridor without bumping into a vacuum cleaner on the floor, appreciate a painting, or feel relaxed in a dimly lighted restaurant. Figure 7-15 illustrates that visibility is central to a larger number of human needs: task performance; mood and atmosphere; visual comfort; aesthetic judgment; health, safety, and well-being; and social communication.

7.4.1. Visibility.

Visibility is the ability to extract information from the field of view, whether that information is the location of a curb or of a flower arrangement. It is a necessary

condition for good-quality lighting. Lighting installations exist to enable sight. For many years this fact led to a heavy emphasis on visibility over all other goals for lighting design. As a result, research was focused in this direction, and we have a good understanding of visibility and its importance. Contrast, luminance, time, and size are the most powerful variables influencing the visibility of objects. Age modifies this relationship; for the older viewer, the task must be larger and brighter and its contrast higher in order to achieve visibility levels equivalent to those of younger viewers. In general, high illuminances can offset visibility losses for tasks of low contrast and small size.

7.4.2. Task Performance.

Task performance is an essential human need. The task is the user's activity, whether measuring the size of a room, washing mud off hands, reading room numbers posted in a corridor to find a doctor's office, or seeing the details in the etchings displayed in a museum. Lighting must enable users to perform the "work" they came to do. Task performance and visual performance are not synonymous; in fact, several nonvisual factors contribute significantly to task performance. Training, motor skills, motivation, and many other human factors interact with visibility to affect the level of task performance. Visual performance, on the other hand, eliminates these factors from consideration in assessing the impact of visual stimuli, including lighting variables, on a behavioral response. Illuminance selection, discussed in its own section below, is largely based on visual performance, not task performance.

7.4.3. Mood and Atmosphere.

Needs for mood and atmosphere encompass the emotional response to the luminous environment. Preference, satisfaction, relaxation, and stimulation are influenced by lighting. These mood states can indirectly influence other behaviors, such as task performance.

7.4.4. Visual Comfort.

Visual comfort is an essential human need that can affect task performance, health and safety, and mood and atmosphere. Office workers may find themselves more fatigued in a glaring lighting installation, but flashing lights in a discotheque can temporarily excite and please that same person.

7.4.5. Aesthetic Judgment.

Aesthetic judgment needs differ from emotional responses. Humans appear to need to make sense of what they see, so the information must be either immediately available in a scene or implied. Lighting can communicate meaning, reinforce rhythmic patterns in the architecture, and enhance color, thereby creating a hierarchy of social significance in the visual field. Lighting can also hinder understanding by introducing patterns that conflict with the underlying scene. One research model that attempts to quantify aesthetic judgments uses four dimensions of appraisal: coherence, legibility, mystery, and complexity. Another uses visual interest and visual lightness (room surface brightness).

These studies conclude that preference for a scene increases when the lighting is non uniform; however, high levels of one quality can reduce levels of another. For example, a scene that is complex may rank low in coherence.

7.4.6. Health, Safety, and Well-Being.

Although they are needs of primary importance, health, safety, and wellbeing are often overlooked. As an example, flicker from some electric lighting can produce a stroboscopic effect with moving machinery, making the machine appear to move at a different rate. Electronic ballasts for fluorescent lamps reduce the perception of flicker, and it also appears that they reduce the incidence of headaches and eyestrain. Safety is an important need, but emergency lighting is only one aspect of it. Lighting also affects the visibility of curbs, stair edges, train platforms, roadway intersections, and labels of critical chemicals and pharmaceuticals. Recent evidence suggests that disruption of the circadian system may have long-term consequences for different types of cancer. This is a new field of research and should be carefully monitored by the lighting designer. The relative importance of these needs differs for each setting. In a factory, aesthetic judgments are likely to be less important than health and safety or task performance. In a restaurant, social and communication needs, aesthetic judgments, mood, and comfort are all important; however, visual tasks such as reading the menu also need to be considered. One of the challenges in lighting design is to determine which human needs are to be served. In some cases, needs conflict and require careful thought to establish priorities.

7.4.7.   **Social Communication.**

Social communication needs include the creation of luminous conditions conducive to such communications in a setting, especially by facial appearance. Much human communication occurs by nonverbal means, but these cues are missed if the lighting distracts from or masks the information. Facial recognition, for example, which is a critical element of security lighting, is influenced not only by the amount of light needed to detect a face, but also by the modeling of facial features created by the pattern of the light and shadow on the subject's face.

7.5.   Lighting quality criteria

From all the issues that should be taken in consideration we can make a first classification between objective parameters and subjective parameters. The first category is made of parameters that could be calculated compared to limit values listed in the appropriate standards. The second category is made of all those parameters connected to all the aspects that could be individually judged in different ways. To development an assessment regarding also the subjective parameters is normally needed a social study on a great number of people to see which is the average response of the people according to the single parameter. Anyway is possible to assume, as we will do in our case studies, a certain number of situation that are commonly connected to positive/negative assessment of the human being. For instance a higher ceiling is normally acknowledge as a positive improvement of the architecture of an office. This parameter affects one side the user perception of the space and on the other side affects the energy consumption assessment of the artificial lighting system.

7.5.1.   **Parameters**

The standard gives a list of requirements that allow making an assessment of the lighting quality environment. Some of those parameters are measurable and other are only explained verbally.

7.5.2.   **Mesurable parameters according to EN 12464-1**

7.5.2.1   Illuminance

The illuminance or better according to EN 12464-1 "Maintained illuminance" is the value below which the average illuminance on the specified surface is not

allowed to fall. In general with the "Objective specified surface" is meant the "Task area" or always according to the standard: "the partial area in the work place in which the visual task is carried out". Another two types of area are pointed out: the working area where many task areas may be located and the surrounding area that is according to EN 12464-1 (Figure 7-16) the area at least 0.5 m wide that can always be seen as a band around the task area. The illuminance values recommended apply to the task area in which the visual task is performed. The task area can be a horizontal (e.g. table), a vertical (e.g. map) or an inclined surface (e.g. drawing table). Task areas typically found in an office are desks, conference tables/ areas, the vertical surfaces of cabinets and shelving systems, and stations for office machinery such as copiers and fax machines. In office illuminance levels higher than 500 lux should be avoided due to glare on VDT

Type of visual task		Illuminance on visual task plane $\bar{E}_m$ lx	UGR_L	R_a	Remarks
Office work	filing, copying	300	19	80	
	communication zones in work rooms	300	19	80	
	writing, typewriting	500	19	80	
	reading, data processing	500	19	80	
	CAD workplaces	500	19	80	
	conference and meeting rooms	500	19	80	lighting adjustable
	reception desk	300	22	80	
	archives	200	25	80	

Figure 7-16 EN 12646-1 raccomended values
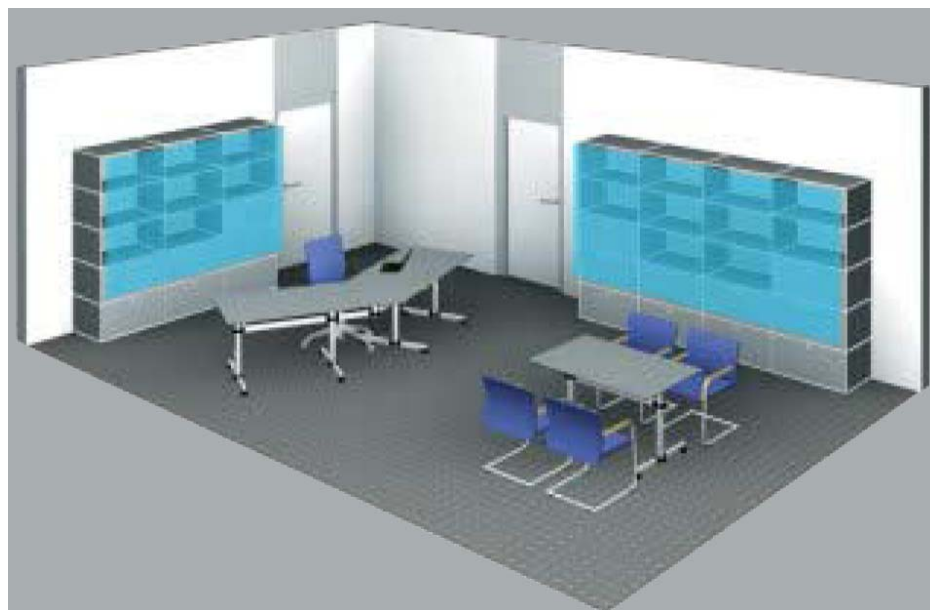
Figure 7-17Vertical task areas in an office: e.g. "cabinet and shelving system surfaces" (blue) illuminance value reference height: starting at 0.5 m rising to 2 m above floor level, width according to objects

7.5.2.2   Glare limitation

Glare is one of the most discomforting of all visual problems. An unshielded general-diffuse lamp or the bright reflection of a window on a VDU screen places considerable strain on our eyes. Glare can have physiological consequences, e.g. impairment of visual acuity. A bright reflection on a screen can obscure information and render it indecipherable. In most cases, glare has at least a psychological impact, causing fatigue and loss of concentration. Visual performance suffers and we make mistakes. A distinction is made between direct glare and reflected glare. Direct glare occurs where a very bright point of light is located in the visual field. Direct glare can be avoided by the use of appropriate luminaires and correct positioning of luminaires and workplaces. Reflected glare occurs as a result of disturbing reflections on shiny or reflective surfaces. These surfaces can be VDU screens, items of furniture or glossy paper. So to avoid reflected glare, it is necessary to look at not only the type and arrangement of luminaires in the room but also the materials and finishes of the office furniture and the positioning of monitors.

The degree of discomfort glare caused by a lighting system can be determined by the UGR method Depending on the difficulty of the visual task, the UGR_L limit should not be exceeded. The following are examples of maximum limits:

Technical drawing	≤ 16
Reading, writing, classrooms, computer work, inspections	≤ 19
Work in industry and craft workshops, reception	≤ 22
Rough work, staircases	≤ 25
Corridors	≤ 28

Figure 7-18 UGR limits for office tasks

Reflected glare on shiny horizontal surfaces (reading matter and paper for writing) is assessed by using the contrast rendering factor (CRF), which can be calculated by special software. For normal office work, a mean value of CRF =

0.7 is high enough; only work involving high-gloss materials calls for a higher value. Reflected glare on VDU screens is the most common cause of complaints. It is effectively avoided where monitors are arranged in such a way that bright surfaces such as windows, luminaires and bright walls cannot be reflected on screens. Where such an arrangement is not possible, the luminance of the surfaces reflected on screens needs to be reduced. For luminaires, EN 12464 sets out luminance limits, which depend on the type and anti-glare design of the computer screen used and apply to all emission angles over 65° to the vertical all-around the vertical axis.

Contrast rendering factors CRF and workplace requirements

Grade	Mean values	Minimum value	Application example
1	over 1,0	0,95	Work involving predominantly glossy materials, e.g. in graphic design offices
2	0,85 to 1,0	0,70	Work where glossy materials are occasionally used, e.g. in offices and schools
3	0,70 to 0,85	0,50	Tasks involving predominantly matt materials

Figure 7-19 Contrast rendering factors CRF

A lighting system should be appropriate for the relevant UGR category. UGR values can be ascertained by the tabular method. UGR tables are available from manufacturers and incorporated in commercial lighting calculation software. For initial luminaire selection, it is advisable to use the tabular value of the reference room (4H / 8H) based on a spacing-to-height ratio of 0.25 Individual UGR values in a lighting system can be calculated using CAD software. This may be useful for designing systems where glare is a critical factor but it does not indicate the standard of glare limitation of the installation as a whole.

As excessively bright light sources in the field of view can cause glare, lamps must also be suitably shielded. For luminaires which are open from below or fitted with a clear enclosure, the shielding angle is defined as the angle between the horizontal and the line of sight below which the luminous parts of the lamp in the luminaire are visible.
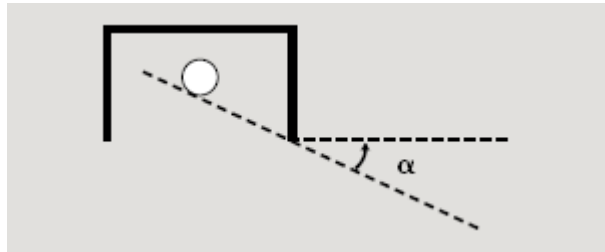
Figure 7-20 Shielding angle alpha

Lamp luminance in cd/m^2	Minimum shielding angle
20,000 to < 50,000 e.g. fluorescent lamps (high output) and compact fluorescent lamps	15°
50,000 to < 500,000 e.g. high-pressure discharge lamps and incandescent lamps with matt and inside-coated bulbs	20°
≥ 500,000 e.g. high-pressure discharge lamps and incandescent lamps with clear bulbs	30°

Figure 7-21 Minimum shielding angles at specific lamp luminances

The minimum shielding angles for the lamp luminances showed (Figure 7-21) need to be observed for all emission planes. They do not apply to luminaires with only a top-side light exit opening or to luminaires mounted below eye level.

7.5.2.3   *Colour appearance and colour rendering*

Ra indicates how well colors are rendered by lamps. Where lamps have a high index of 90 or more, all colors are rendered very accurately; where the index is lower, the colors we perceive are corrupted. Reds then look orange, greens appear yellow. Lamps are divided for convenience into color rendering categories. Most lamps have a color rendering index of over 80 and thus render colors well enough for us to perceive them as natural. Incandescent lamps, tungstenhalogen lamps, certain metal halide lamps and a number of fluorescent lamps have a color rendering index of over 90, which means they render all colors very accurately.

7.5.2.4   Distribution of illuminance

Uniformity of illuminance or luminance is another quality feature. It is expressed s the ratio of minimum to mean illuminance ($g_1 = E_{min} / E$) or, in street lighting, as the ratio of minimum to mean luminance ($U_0 = L_{min} / L$). In certain applications, the ratio of minimum to maximum illuminance $g_2 = E_{min} / E_{max}$ is important. In the task area the uniformity should be always more than 0.7. In the working areas should be always more than 0.6 and in the sourrounding area should be always more than 0.5 (Figure 7-22).
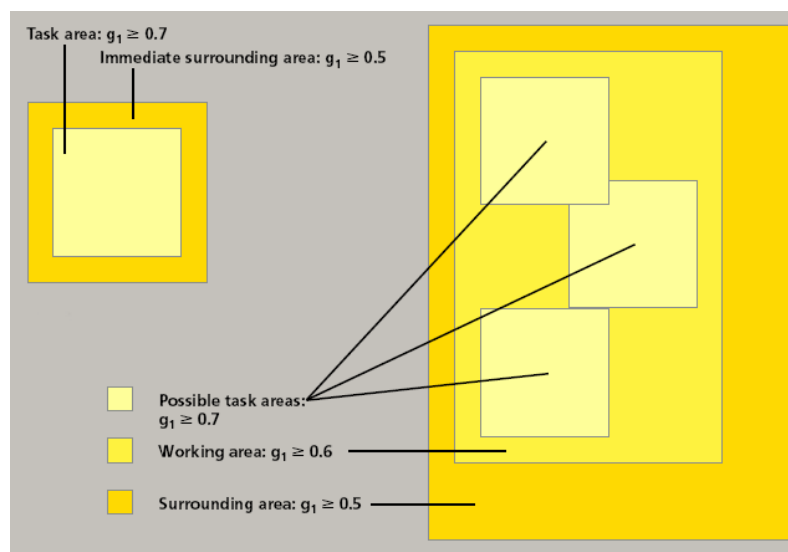
Figure 7-22 Uniformity levels in different areas

7.5.2.5   Low luminance

As well as rating direct glare due to excessively luminant surfaces, special attention needs to be paid to avoiding reflected glare, which is the glare caused by light reflecting from shiny surfaces. Reflections of excessively bright luminous parts of a luminaire can seriously interfere with work at a screen or even at a keyboard. Care needs to be taken to arrange suitable luminaires so that no disturbing reflections are created. In DIN EN 12464-1, luminance limits are specified for luminaires which could reflect along normal lines of sight from a screen inclined at up to 15°. As a general rule, 1,000 cd/m^2 needs to be observed for positive display LCD or CRT monitors with a good anti-reflective or anti-glare finish and 200 cd/m^2 for negative display CRT monitors such as those used at

CAD workstations. The luminances specified must not be exceeded at elevation angles ≥ 65° from the downward vertical in any radiation plane.

VDUs	mean luminance of luminaires and surfaces which reflect on screens
Positive display VDUs	≤ 1000 cd/m^2
Negative display VDUs with high-grade anti-reflective system Evidence of test certificate required	
Negative display VDUs with lower-grade anti-reflective system	≤ 200 cd/m^2

Figure 7-23 Mean luminance of luminaires and surfaces which reflect on screens.
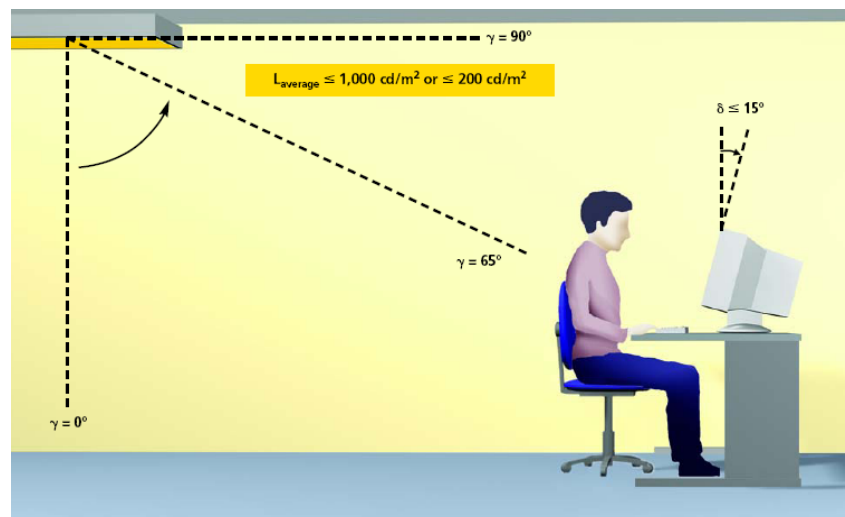
Figure 7-24 Critical zone of radiation ($\gamma \geq$ 65°)for luminance which could give rise to reflected glare on screen.

7.5.2.6   *Light direction,effects of shadow and modelling (BGI 856 DIN 5035-7)*

It takes directional lighting and modelling to permit 3D projection, to give objects depth. A bright room with nothing but diffuse lighting and no shadows makes a monotonous impression; the lack of orientation, poor definition of objects and difficulty in gauging distances make us feel uncomfortable.

In contrast, point-like light sources with extremely directional beams produce hardedged   shadows.   Such   harsh   shadow   renders   virtually   everything

unrecognizable; it can even cause potentially dangerous optical illusions, e.g. where tools are used, machines are operated or stairs need to be negotiated.

Direction of light and modelling also help define visual ambience. A good ratio of diffuse light (e.g. from indirect lighting components) to directional light (e.g. from direct louver luminaires or downlights) makes for agreeable modelling. Direction of light is generally defined by daylight entering the room through a window from a particular direction. Excessively deep shadowing, e.g. in front of a writing hand, can be offset by artificial lighting. In offices where desk arrangements are geared to incident daylight, it is advisable to control daylight incidence by means of window blinds and to use continuous rows of luminaires on separate switching circuits to lighten disturbing shadows. Where luminaires are arranged parallel to the window wall, the rear row of luminaires can lighten any dark shadows that might occur during the day. As daylight fades, the front row of luminaires near the windows can be partially or fully activated to make up for the loss of natural light.

a)   b)

Figure 7-25 Strong shadows make the visual communication more diffcoult b), sufficient cylindrical illuminance helps the visual communication a).

7.5.3. Non mesurables parameters according to EN 12464-1

- Avoidance of flicker and stroboscopic effects

- Appropriate control of veiling reflections and reflected glare

- Proper distribution of vertical luminance in the room

- Special attention of visual communication in lighting faces

- Special Health issues

7.5.4. Other non mesurables parameters

7.5.4.1 *Space*

The variety of office type require a deeper designer knowledge regarding a wide range of multidisciplinary aspects according to the continuous development due to the steady introduction of new technologies in the work process and to on the growth of user's needs. (Figure 7-26) It's not possible to expect a similarity between the different concepts regarding not only different requirements of flexibility and of the involved technologies but also all the specific factors that have to fulfill every peculiar activity of the user. Ergonomics is the matching of the work environment, tools, and the people who use them. Good ergonomics promotes productivity, minimizes physical distractions, and reduces the risk of injury and illness. Unlike many occupational safety and health issues, ergonomic considerations vary highly with the person, his or her physical characteristics and preferred working style. Ergonomics is the scientific study of the human at work. Ergonomics deals with many issues, starting with a single employee and their workstation, and expanding out to include an entire department. Most of the organizational and environmental factors, as well as the selection of workstation furniture, are under management control. Many of the factors related to the arrangement of the workstation and work habits are under each employee's control. The focus of ergonomics is always on designing for the individual employee, who brings unique characteristics with her or him to the job.

7.5.4.2 *Personal lighting and personal preference.*

Personal lighting is the possibility to switch personally the lights on and off. This kind of liberty gives the user a sense of wellness. This kind of light management doesn't fit with an automatic light management that would be energy saving oriented. A light management system would drive the lighting system according to the presence and according to the external daylight level. Nevertheless is possible to combine both. The new management system as the DALI allows to control basically all the luminaires through an "energy saving logic" and to leave each user to drive manually "his" luminaires. This kind of flexibility affect actually the "energy saving" efforts of the systems. A DALI system allows moreover managing different scenes according to the user's needs. To exploit this kind of opportunity should be planned a system that has the chance to generate different scenarios with different kind of luminaires. This kind of possibility affects the energy consumption according to higher needs of luminaires of different types.

7.6. Lighting quality classes according to EN 15193

An approach to evaluate the ergonomic quality level of an installation is to quantify the individual quality criteria. According to the EN 15193 the parameters chosen are:

	Lighting design criteria class		
	$*$	$**$	$***$
Maintained illuminance on horizontal visual tasks ($E_{M\,horizontal}$)	☑	☑	☑
Appropriate control of discomfort glare (UGR)	☑	☑	☑
Avoidance of flicker and stroboscopic effects	✓	✓	✓
Appropriate control of veiling reflections and reflected glare		✓	✓
Improved colour rendering		☑	☑
Avoidance of harsh shadows or too diffuse light in order to provide good modelling		✓	✓
Proper luminance distribution in the room ($E_{vertical}$)		✓	✓
Special attention of visual communication in lighting faces ($E_{cylindrical}$)			✓
Special attention to health issues (Note)			✓
☑: has to comply with required values from Tables 5.3 in EN 12464-1 ✓: has to conform to verbally described requirements from EN 12464-1 NOTE health issues may even require much higher illuminances and therefore higher W/m^2 The maximum power density load (PN) connected to the lighting design class is given in the benchmark Table F.1.			

Figure 7-27 EN 15193 lighting quality parameters

8. Results

8.1. Preliminary case studies

In the first part of this study it has been prepared an Excel spreadsheet table to collect several different case studies. On this excel it has been developed a tool based on the DIN 18599-4 for the calculation of the installed power for lighting. Different types of offices, from cellular office ($12m^2$) up to medium sized group offices ($400m^2$) have been taken in consideration. Each case refers to a particular surface. Different geometries have been taken in consideration by width and length of the rooms to point out the influence of the index room. Any represented case is listed on a line of the excel table and represents a preliminary investigated case study. For each case study it has been calculated the specific installed power that is needed to accomplish the requirement for offices lighting according to the EN 12464-1. Those cases are classified according to different characteristics. Different lot of cases differs only for one variable. So on the base of the whole lot of case studies sub groups of case studies can be classified. For instance

The sub groups can be classified according to:

- Number of square meters per user

    o 8 m^2/User

    o 10m^2/User

    o 12m^2/User

- Ceiling height:

    o h_c = 2,7 m

    o h_c = 3 m

    o h_c= 3,5 m

- Lighting strategy:

    o Direct

    o Indirect

          o   Direct/Indirect

Two different kind of strategy have been taken in consideration for the lighting management:

- Manual on/off switching without presence sensor

- Automatic on/off switching driven from presence sensor with dimming of the lights driven from an external light sensor.

In all the preliminary case studies fluorescent linear lamps have been chosen. In the following real case studies fluorescent linear lamps plus compact fluorescent lamps have been selected. The luminaires are installed "in-ceiling" (h=2,7 m; h=3 m) or pendant for presented cases where the higher ceiling variation has been taken in consideration of height. The height of the task is always 0,85 m.

Due to the raise of the "lines" of the excel assessment table it has been decided to pick out only those situation that could represent more realistically the refined and the real cases presented in the following sections. In the conclusion section those results are compared with outcoming assessment from the simulations.

The excel assessment table evaluates the specific installed power according to the DIN 18599. This standard has been chosen as assessment method as far it is the only one that is included in a valid standard. It helps to represent with a good accuracy and in a quite simple way the very most important value that is needed to start all the energy assessment evaluation. The consumed energy in a lighting system is always a function of this value. The lower is this value the lower will be the consumed energy according to the geographic position and the environmental situation of the site, according to the characteristics of the envelope and according to the lighting management strategies (BMS or automation level).

The European standard does not give any prescription to calculate the specific installed power. This standard foresees to detect the installed power that is estimated in the lighting design, moreover gives a method to assess the energy consumption. This standard gives a benchmark for the specific installed power for different classes of lighting quality according to two different lighting management systems for cases with or without constant illuminance control system:

- Manual

- Automatic

Specific surface	Number of work places	AREA	HEIGHT	LENGTH	WIDTH	ROOM INDEX	HEIGHT OF THE LUMINARIES	TASK HEIGHT	DIRECT / INDIRECT k	DIRECT k	BALLAST TYPE		kA	kL	k_{RD}	$k_{RD/I}$	K_{RI}	DIRECT Pj	DIRECT/INDIRECT Pj	INDIRECT Pj
8	1	8	2,7	3	2,67	0,52	2,20	0,85	1,046	0,763	EB	6	0,80	1,000	0,930	0,900	0,850	18,6	21,6	34,0
8	2	16	2,7	3	5,33	0,71	2,20	0,85	1,422	1,038	EB	6	0,80	1,000	0,770	0,734	0,618	15,4	17,6	24,7
8	2	16	2,7	4	4,00	0,74	2,20	0,85	1,481	1,081	EB	6	0,80	1,000	0,770	0,734	0,618	15,4	17,6	24,7
8	3	24	2,7	3	8,00	0,81	2,20	0,85	1,616	1,179	EB	6	0,80	1,000	0,730	0,704	0,584	14,6	16,9	23,4
8	3	24	2,7	4	6,00	0,89	2,20	0,85	1,778	1,297	EB	6	0,80	1,000	0,680	0,688	0,568	13,6	16,5	22,7
8	3	24	2,7	5	4,80	0,91	2,20	0,85	1,814	1,324	EB	6	0,80	1,000	0,660	0,672	0,552	13,2	16,1	22,1
8	4	32	2,7	3	10,67	0,87	2,20	0,85	1,734	1,266	EB	6	0,80	1,000	0,680	0,688	0,568	13,6	16,5	22,7
8	4	32	2,7	4	8,00	0,99	2,20	0,85	1,975	1,441	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
8	4	32	2,7	5	6,40	1,04	2,20	0,85	2,079	1,517	EB	6	0,80	1,000	0,630	0,640	0,520	12,6	15,4	20,8
8	4	32	2,7	6	5,33	1,05	2,20	0,85	2,092	1,526	EB	6	0,80	1,000	0,630	0,640	0,520	12,6	15,4	20,8
8	5	40	2,7	3	13,33	0,91	2,20	0,85	1,814	1,324	EB	6	0,80	1,000	0,660	0,672	0,552	13,2	16,1	22,1
8	5	40	2,7	4	10,00	1,06	2,20	0,85	2,116	1,544	EB	6	0,80	1,000	0,630	0,640	0,520	12,6	15,4	20,8
8	5	40	2,7	5	8,00	1,14	2,20	0,85	2,279	1,663	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
8	5	40	2,7	6	6,67	1,17	2,20	0,85	2,339	1,707	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
8	5	40	2,7	7	5,71	1,17	2,20	0,85	2,330	1,701	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
8	8	64	2,7	3	21,33	0,97	2,20	0,85	1,948	1,422	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
8	8	64	2,7	4	16,00	1,19	2,20	0,85	2,370	1,730	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
8	8	64	2,7	5	12,80	1,33	2,20	0,85	2,663	1,944	EB	6	0,80	1,000	0,590	0,580	0,470	11,8	13,9	18,8
8	8	64	2,7	6	10,67	1,42	2,20	0,85	2,844	2,076	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
8	8	64	2,7	7	9,14	1,47	2,20	0,85	2,937	2,143	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
8	1	8	3	3	2,67	0,47	2,50	0,85	0,856	0,657	EB	6	0,80	1,000	1,025	1,015	1,015	20,5	24,4	40,6
8	2	16	3	3	5,33	0,64	2,50	0,85	1,164	0,893	EB	6	0,80	1,000	0,855	0,856	0,786	17,1	20,5	31,4
8	2	16	3	4	4,00	0,67	2,50	0,85	1,212	0,930	EB	6	0,80	1,000	0,820	0,812	0,722	16,4	19,5	28,9
8	3	24	3	3	8,00	0,73	2,50	0,85	1,322	1,015	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
8	3	24	3	4	6,00	0,80	2,50	0,85	1,455	1,116	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	3	24	3	5	4,80	0,82	2,50	0,85	1,484	1,139	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	4	32	3	3	10,67	0,78	2,50	0,85	1,419	1,089	EB	6	0,80	1,000	0,770	0,734	0,618	15,4	17,6	24,7
8	4	32	3	4	8,00	0,89	2,50	0,85	1,616	1,240	EB	6	0,80	1,000	0,698	0,704	0,584	14,0	16,9	23,4
8	4	32	3	5	6,40	0,94	2,50	0,85	1,701	1,306	EB	6	0,80	1,000	0,660	0,688	0,568	13,2	16,5	22,7
8	4	32	3	6	5,33	0,94	2,50	0,85	1,711	1,313	EB	6	0,80	1,000	0,660	0,688	0,568	13,2	16,5	22,7
8	5	40	3	3	13,33	0,82	2,50	0,85	1,484	1,139	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	5	40	3	4	10,00	0,95	2,50	0,85	1,732	1,329	EB	6	0,80	1,000	0,660	0,688	0,568	13,2	16,5	22,7
8	5	40	3	5	8,00	1,03	2,50	0,85	1,865	1,431	EB	6	0,80	1,000	0,640	0,672	0,552	12,8	16,1	22,1
8	5	40	3	6	6,67	1,05	2,50	0,85	1,914	1,469	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
8	5	40	3	7	5,71	1,05	2,50	0,85	1,907	1,463	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
8	8	64	3	3	21,33	0,88	2,50	0,85	1,594	1,223	EB	6	0,80	1,000	0,698	0,720	0,600	14,0	17,3	24,0
8	8	64	3	4	16,00	1,07	2,50	0,85	1,939	1,488	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
8	8	64	3	5	12,80	1,20	2,50	0,85	2,179	1,672	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
8	8	64	3	6	10,67	1,28	2,50	0,85	2,327	1,786	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
8	8	64	3	7	9,14	1,32	2,50	0,85	2,403	1,844	EB	6	0,80	1,000	0,600	0,640	0,520	12,0	15,4	20,8
8	1	8	3,5	3	2,67	0,40	3,00	0,85	0,657	0,533	EB	6	0,80	1,000	1,080	1,235	0,855	21,6	29,6	34,2
8	2	16	3,5	3	5,33	0,55	3,00	0,85	0,893	0,725	EB	6	0,80	1,000	0,970	1,015	1,015	19,4	24,4	40,6
8	2	16	3,5	4	4,00	0,57	3,00	0,85	0,930	0,755	EB	6	0,80	1,000	0,930	0,970	0,950	18,6	23,3	38,0
8	3	24	3,5	3	8,00	0,62	3,00	0,85	1,015	0,823	EB	6	0,80	1,000	0,890	0,900	0,850	17,8	21,6	34,0
8	3	24	3,5	4	6,00	0,69	3,00	0,85	1,116	0,906	EB	6	0,80	1,000	0,820	0,856	0,786	16,4	20,5	31,4
8	3	24	3,5	5	4,80	0,70	3,00	0,85	1,139	0,924	EB	6	0,80	1,000	0,820	0,856	0,786	16,4	20,5	31,4
8	4	32	3,5	3	10,67	0,67	3,00	0,85	1,089	0,884	EB	6	0,80	1,000	0,855	0,900	0,850	17,1	21,6	34,0
8	4	32	3,5	4	8,00	0,76	3,00	0,85	1,240	1,006	EB	6	0,80	1,000	0,770	0,812	0,722	15,4	19,5	28,9
8	4	32	3,5	5	6,40	0,80	3,00	0,85	1,306	1,059	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
8	4	32	3,5	6	5,33	0,81	3,00	0,85	1,313	1,065	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
8	5	40	3,5	3	13,33	0,70	3,00	0,85	1,139	0,924	EB	6	0,80	1,000	0,820	0,856	0,786	16,4	20,5	31,4
8	5	40	3,5	4	10,00	0,82	3,00	0,85	1,329	1,078	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
8	5	40	3,5	5	8,00	0,88	3,00	0,85	1,431	1,161	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	5	40	3,5	6	6,67	0,90	3,00	0,85	1,469	1,192	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	5	40	3,5	7	5,71	0,90	3,00	0,85	1,463	1,187	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
8	8	64	3,5	3	21,33	0,75	3,00	0,85	1,223	0,993	EB	6	0,80	1,000	0,795	0,812	0,722	15,1	19,5	28,9
8	8	64	3,5	4	16,00	0,91	3,00	0,85	1,488	1,208	EB	6	0,80	1,000	0,698	0,734	0,618	14,0	17,6	24,7
8	8	64	3,5	5	12,80	1,03	3,00	0,85	1,672	1,357	EB	6	0,80	1,000	0,660	0,704	0,584	13,2	16,9	23,4
8	8	64	3,5	6	10,67	1,10	3,00	0,85	1,786	1,449	EB	6	0,80	1,000	0,640	0,688	0,568	12,8	16,5	22,7
8	8	64	3,5	7	9,14	1,13	3,00	0,85	1,844	1,496	EB	6	0,80	1,000	0,640	0,672	0,552	12,8	16,1	22,1

Tab. 2 Preliminary studies assessment table (I) 8m^2 per user

Figure 8-1 Specific installed d power vs. Room index for different work places case with 8 m² per user.

Specific surface	Number of work places	AREA	HEIGHT	LENGTH	WIDTH	ROOM INDEX	HEIGHT OF THE LUMINARIES	TASK HEIGHT	DIRECT / INDIRECT	DIRECT	BALLAST TYPE		kA	kL	k_{RD}	$k_{RD/I}$	K_{RI}	DIRECT	DIRECT/INDIRECT	INDIRECT
									k	k								Pj	Pj	Pj
10	3	30	2,7	4	7,50	0,97	2,20	0,85	1,932	1,410	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
10	3	30	2,7	5	6,00	1,01	2,20	0,85	2,020	1,474	EB	6	0,80	1,000	0,640	0,640	0,520	12,8	15,4	20,8
10	4	40	2,7	3	13,33	0,91	2,20	0,85	1,814	1,324	EB	6	0,80	1,000	0,660	0,672	0,552	13,2	16,1	22,1
10	4	40	2,7	4	10,00	1,06	2,20	0,85	2,116	1,544	EB	6	0,80	1,000	0,630	0,640	0,520	12,6	15,4	20,8
10	4	40	2,7	5	8,00	1,14	2,20	0,85	2,279	1,663	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
10	4	40	2,7	6	6,67	1,17	2,20	0,85	2,339	1,707	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
10	6	60	2,7	3	20,00	0,97	2,20	0,85	1,932	1,410	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
10	6	60	2,7	4	15,00	1,17	2,20	0,85	2,339	1,707	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
10	6	60	2,7	5	12,00	1,31	2,20	0,85	2,614	1,908	EB	6	0,80	1,000	0,590	0,580	0,470	11,8	13,9	18,8
10	6	60	2,7	6	10,00	1,39	2,20	0,85	2,778	2,027	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
10	6	60	2,7	7	8,57	1,43	2,20	0,85	2,854	2,083	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
10	8	80	2,7	3	26,67	1,00	2,20	0,85	1,998	1,458	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
10	8	80	2,7	4	20,00	1,23	2,20	0,85	2,469	1,802	EB	6	0,80	1,000	0,600	0,640	0,520	12,0	15,4	20,8
10	8	80	2,7	5	16,00	1,41	2,20	0,85	2,822	2,059	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
10	8	80	2,7	6	13,33	1,53	2,20	0,85	3,065	2,237	EB	6	0,80	1,000	0,580	0,560	0,440	11,6	13,4	17,6
10	8	80	2,7	7	11,43	1,61	2,20	0,85	3,216	2,347	EB	6	0,80	1,000	0,580	0,560	0,440	11,6	13,4	17,6
10	3	30	3	3	10,00	0,77	2,50	0,85	1,399	1,073	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
10	3	30	3	4	7,50	0,87	2,50	0,85	1,581	1,213	EB	6	0,80	1,000	0,698	0,720	0,600	14,0	17,3	24,0
10	3	30	3	5	6,00	0,91	2,50	0,85	1,653	1,268	EB	6	0,80	1,000	0,680	0,704	0,584	13,6	16,9	23,4
10	4	40	3	3	13,33	0,82	2,50	0,85	1,484	1,139	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
10	4	40	3	4	10,00	0,95	2,50	0,85	1,732	1,329	EB	6	0,80	1,000	0,660	0,688	0,568	13,2	16,5	22,7
10	4	40	3	5	8,00	1,03	2,50	0,85	1,865	1,431	EB	6	0,80	1,000	0,640	0,672	0,552	12,8	16,1	22,1
10	4	40	3	6	6,67	1,05	2,50	0,85	1,914	1,469	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
10	6	60	3	3	20,00	0,87	2,50	0,85	1,581	1,213	EB	6	0,80	1,000	0,698	0,720	0,600	14,0	17,3	24,0
10	6	60	3	4	15,00	1,05	2,50	0,85	1,914	1,469	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
10	6	60	3	5	12,00	1,18	2,50	0,85	2,139	1,642	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
10	6	60	3	6	10,00	1,25	2,50	0,85	2,273	1,744	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
10	6	60	3	7	8,57	1,28	2,50	0,85	2,335	1,792	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
10	3	30	3,5	4	7,50	0,75	3,00	0,85	1,213	0,984	EB	6	0,80	1,000	0,795	0,812	0,722	15,9	19,5	28,9
10	3	30	3,5	5	6,00	0,78	3,00	0,85	1,268	1,029	EB	6	0,80	1,000	0,770	0,790	0,690	15,4	19,0	27,6
10	4	40	3,5	3	13,33	0,70	3,00	0,85	1,139	0,924	EB	6	0,80	1,000	0,820	0,856	0,786	16,4	20,5	31,4
10	4	40	3,5	4	10,00	0,82	3,00	0,85	1,329	1,078	EB	6	0,80	1,000	0,770	0,762	0,654	15,4	18,3	26,2
10	4	40	3,5	5	8,00	0,88	3,00	0,85	1,431	1,161	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
10	4	40	3,5	6	6,67	0,90	3,00	0,85	1,469	1,192	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
10	5	50	3,5	3	16,67	0,73	3,00	0,85	1,182	0,959	EB	6	0,80	1,000	0,795	0,856	0,786	15,9	20,5	31,4
10	5	50	3,5	4	12,50	0,87	3,00	0,85	1,409	1,144	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
10	5	50	3,5	5	10,00	0,95	3,00	0,85	1,550	1,258	EB	6	0,80	1,000	0,680	0,720	0,600	13,6	17,3	24,0
10	5	50	3,5	6	8,33	1,00	3,00	0,85	1,622	1,316	EB	6	0,80	1,000	0,660	0,704	0,584	13,2	16,9	23,4
10	5	50	3,5	7	7,14	1,01	3,00	0,85	1,644	1,334	EB	6	0,80	1,000	0,660	0,704	0,584	13,2	16,9	23,4
10	8	80	3,5	3	26,67	0,77	3,00	0,85	1,254	1,018	EB	6	0,80	1,000	0,770	0,790	0,690	15,4	19,0	27,6
10	8	80	3,5	4	20,00	0,95	3,00	0,85	1,550	1,258	EB	6	0,80	1,000	0,680	0,720	0,600	13,6	17,3	24,0
10	8	80	3,5	5	16,00	1,09	3,00	0,85	1,772	1,438	EB	6	0,80	1,000	0,640	0,688	0,568	12,8	16,5	22,7
10	8	80	3,5	6	13,33	1,18	3,00	0,85	1,925	1,561	EB	6	0,80	1,000	0,630	0,656	0,536	12,6	15,7	21,4
10	8	80	3,5	7	11,43	1,24	3,00	0,85	2,019	1,638	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
10	8	80	3,5	8	10,00	1,27	3,00	0,85	2,067	1,677	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
10	8	80	3,5	7	11,43	1,24	3,00		2,019	1,638	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
10	8	80	3,5	8	10,00	1,27	3,00		2,067	1,677	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8

Tab. 3 Preliminary studies assessment table (II) 10 m^2 per user

Figure 8-2 Specific installed d power vs. Room index for different work places case with 10 m² per user.

Specific surface	Number of work places	AREA	HEIGHT	LENGTH	WIDTH	ROOM INDEX	HEIGHT OF THE LUMINARIES	TASK HEIGHT	DIRECT / INDIRECT	DIRECT	BALLAST TYPE		kA	kL	k_{RD}	$k_{RD/I}$	K_{RI}	DIRECT	DIRECT/INDIRECT	INDIRECT
									k	k								Pj	Pj	Pj
12	1	12	2,7	3	4,00	0,63	2,20	0,85	1,270	0,927	EB	6	0,80	1,000	0,820	0,790	0,690	16,4	19,0	27,6
12	2	24	2,7	3	8,00	0,81	2,20	0,85	1,616	1,179	EB	6	0,80	1,000	0,730	0,704	0,584	14,6	16,9	23,4
12	2	24	2,7	4	6,00	0,89	2,20	0,85	1,778	1,297	EB	6	0,80	1,000	0,680	0,688	0,568	13,6	16,5	22,7
12	3	36	2,7	3	12,00	0,89	2,20	0,85	1,778	1,297	EB	6	0,80	1,000	0,680	0,688	0,568	13,6	16,5	22,7
12	3	36	2,7	4	9,00	1,03	2,20	0,85	2,051	1,497	EB	6	0,80	1,000	0,640	0,640	0,520	12,8	15,4	20,8
12	3	36	2,7	5	7,20	1,09	2,20	0,85	2,186	1,595	EB	6	0,80	1,000	0,630	0,640	0,520	12,6	15,4	20,8
12	4	48	2,7	3	16,00	0,94	2,20	0,85	1,871	1,366	EB	6	0,80	1,000	0,660	0,672	0,552	13,2	16,1	22,1
12	4	48	2,7	4	12,00	1,11	2,20	0,85	2,222	1,622	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
12	4	48	2,7	5	9,60	1,22	2,20	0,85	2,435	1,777	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
12	4	48	2,7	6	8,00	1,27	2,20	0,85	2,540	1,853	EB	6	0,80	1,000	0,600	0,580	0,470	12,0	13,9	18,8
12	5	60	2,7	3	20,00	0,97	2,20	0,85	1,932	1,410	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
12	5	60	2,7	4	15,00	1,17	2,20	0,85	2,339	1,707	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
12	5	60	2,7	5	12,00	1,31	2,20	0,85	2,614	1,908	EB	6	0,80	1,000	0,590	0,580	0,470	11,8	13,9	18,8
12	5	60	2,7	6	10,00	1,39	2,20	0,85	2,778	2,027	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
12	5	60	2,7	7	8,57	1,43	2,20	0,85	2,854	2,083	EB	6	0,80	1,000	0,580	0,580	0,470	11,6	13,9	18,8
12	5	60	3	3	20,00	0,87	2,50	0,85	1,581	1,213	EB	6	0,80	1,000	0,698	0,720	0,600	14,0	17,3	24,0
12	5	60	3	4	15,00	1,05	2,50	0,85	1,914	1,469	EB	6	0,80	1,000	0,640	0,656	0,536	12,8	15,7	21,4
12	5	60	3	5	12,00	1,18	2,50	0,85	2,139	1,642	EB	6	0,80	1,000	0,620	0,640	0,520	12,4	15,4	20,8
12	5	60	3	6	10,00	1,25	2,50	0,85	2,273	1,744	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
12	5	60	3	7	8,57	1,28	2,50	0,85	2,335	1,792	EB	6	0,80	1,000	0,610	0,640	0,520	12,2	15,4	20,8
12	5	60	3,5	3	20,00	0,75	3,00	0,85	1,213	0,984	EB	6	0,80	1,000	0,795	0,812	0,722	15,9	19,5	28,9
12	5	60	3,5	4	15,00	0,90	3,00	0,85	1,469	1,192	EB	6	0,80	1,000	0,730	0,734	0,618	14,6	17,6	24,7
12	5	60	3,5	5	12,00	1,01	3,00	0,85	1,642	1,332	EB	6	0,80	1,000	0,660	0,704	0,584	13,2	16,9	23,4
12	5	60	3,5	6	10,00	1,07	3,00	0,85	1,744	1,415	EB	6	0,80	1,000	0,640	0,688	0,568	12,8	16,5	22,7
12	5	60	3,5	7	8,57	1,10	3,00	0,85	1,792	1,454	EB	6	0,80	1,000	0,640	0,688	0,568	12,8	16,5	22,7

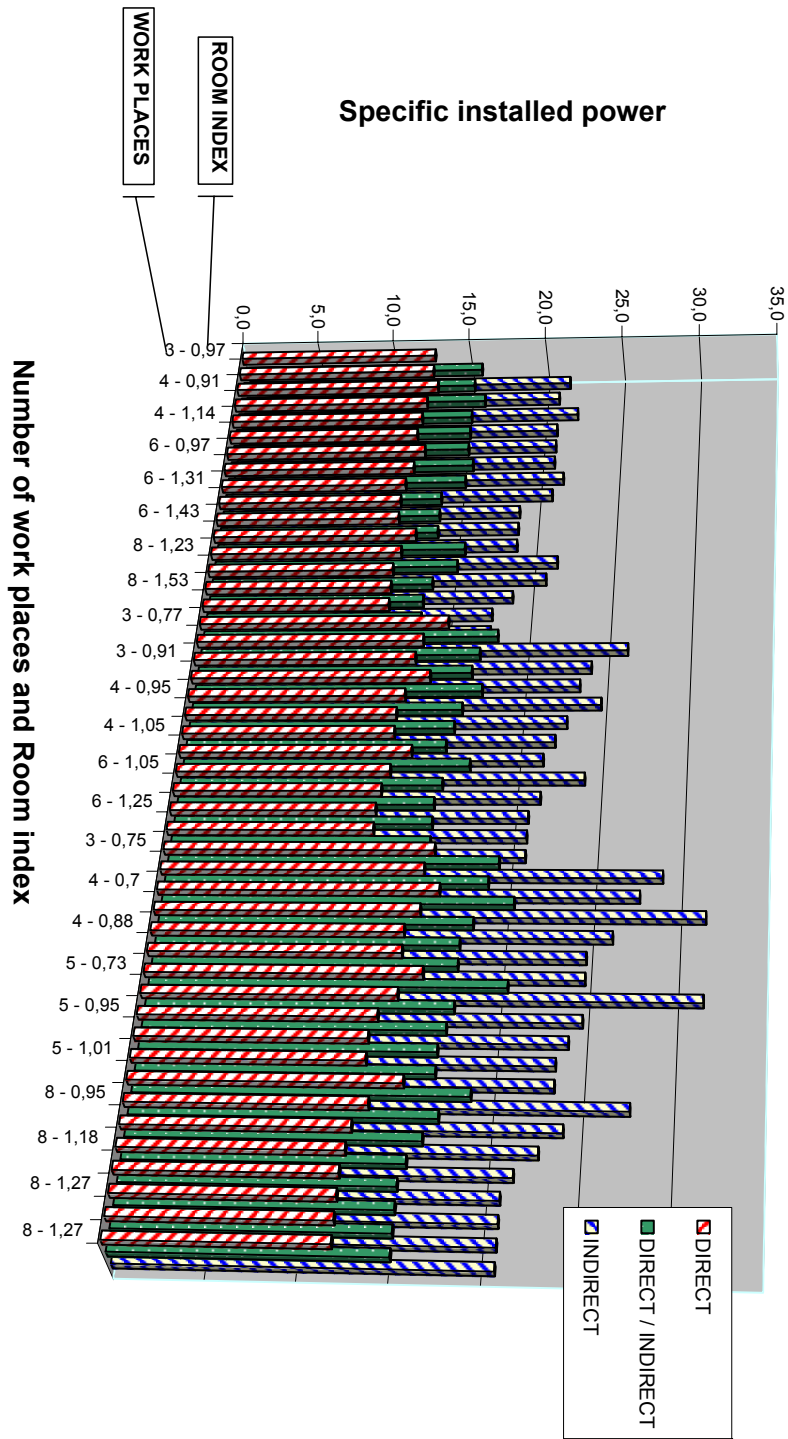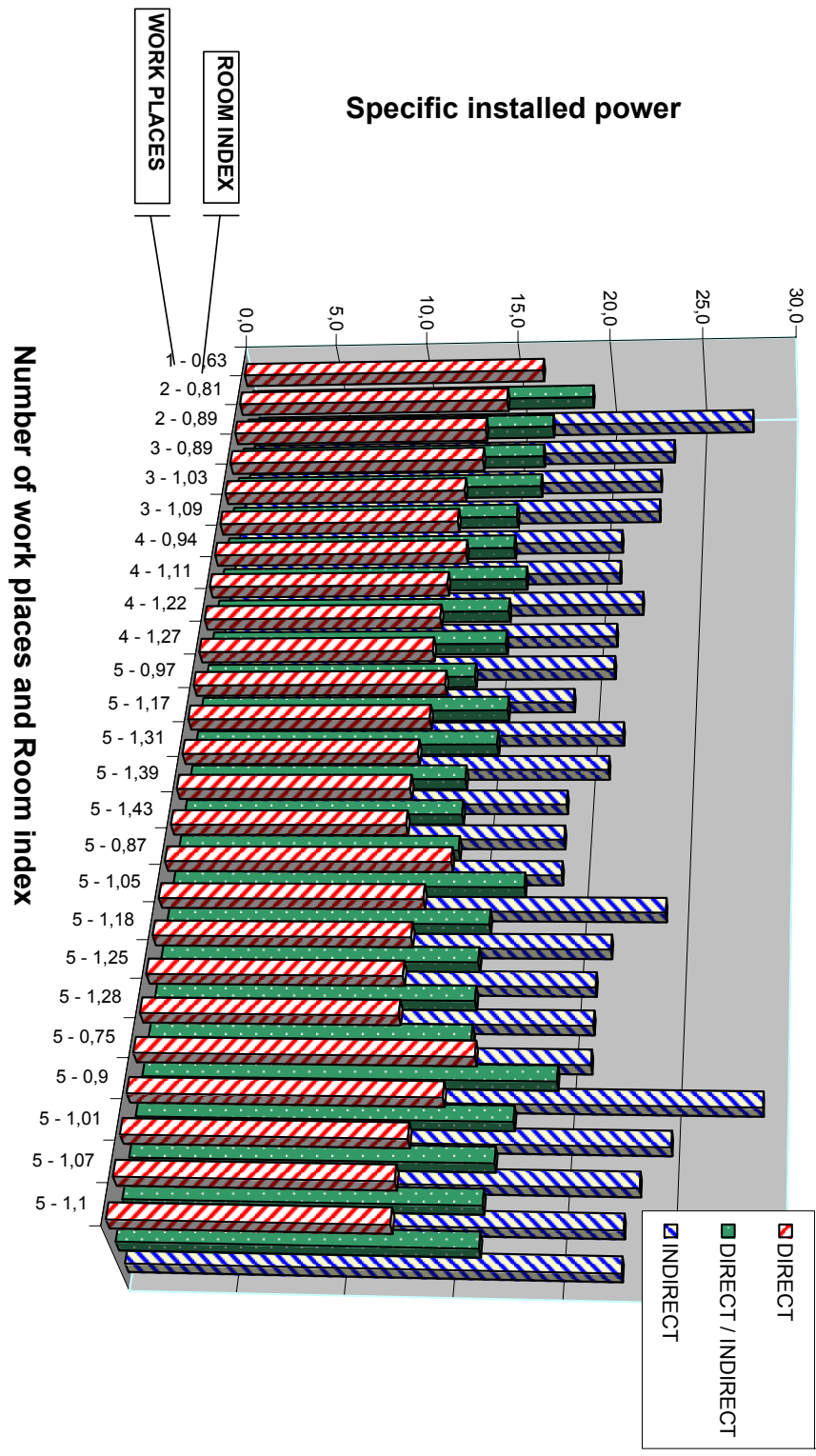*Tab. 4 Preliminary studies assessment table (III) 12 m^2 per user*

Figure 8-3 Specific installed d power vs. Room index for different work places case with 12 m² per user.

Specific surface	Number of work places	AREA	HEIGHT	LENGTH	WIDTH	ROOM INDEX	HEIGHT OF THE LUMINARIES	TASK HEIGHT	DIRECT / INDIRECT k	DIRECT k	BALLAST TYPE		k_A	k_L	k_{RD}	k_{RDM}	K_{RI}	DIRECT P_j	DIRECT/INDIRECT P_j	INDIRECT P_j
8	10	80	2,7	8	10,00	1,65	2,2	0,85	3,2922	2,4024	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
8	15	120	2,7	4	30,00	1,31	2,2	0,85	2,6144	1,9078	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
8	15	120	2,7	6	20,00	1,71	2,2	0,85	3,4188	2,4948	EB	6	0,8	1	0,58	0,58	0,44	11,6	13,44	17,6
8	15	120	2,7	8	15,00	1,93	2,2	0,85	3,8647	2,8202	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	15	120	2,7	10	12,00	2,02	2,2	0,85	4,0404	2,9484	EB	6	0,8	1	0,55	0,53	0,42	11	12,72	16,8
8	20	160	2,7	4	40,00	1,35	2,2	0,85	2,6936	1,9656	EB	6	0,8	1	0,59	0,58	0,44	11,8	13,92	18,8
8	20	160	2,7	6	26,67	1,81	2,2	0,85	3,6281	2,6475	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	2,7	8	20,00	2,12	2,2	0,85	4,2328	3,0888	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	20	160	2,7	10	16,00	2,28	2,2	0,85	4,5584	3,3264	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	20	160	2,7	12	13,33	2,34	2,2	0,85	4,6784	3,4139	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	2,7	4	50,00	1,37	2,2	0,85	2,7435	2,002	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	25	200	2,7	6	33,33	1,88	2,2	0,85	3,7665	2,7485	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	2,7	8	25,00	2,24	2,2	0,85	4,4693	3,276	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	2,7	10	20,00	2,47	2,2	0,85	4,9383	3,6036	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	2,7	12	16,67	2,58	2,2	0,85	5,168	3,7712	EB	6	0,8	1	0,53	0,53	0,39	10,6	12,72	15,6
8	25	200	2,7	14	14,29	2,62	2,2	0,85	5,2376	3,822	EB	6	0,8	1	0,53	0,53	0,39	10,6	12,72	15,6
8	10	80	3	4	20,00	1,11	2,5	0,85	2,0202	1,5604	EB	6	0,8	1	0,63	0,64	0,52	12,6	15,36	20,8
8	10	80	3	6	13,33	1,38	2,5	0,85	2,5078	1,9246	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
8	10	80	3	8	10,00	1,48	2,5	0,85	2,6936	2,0672	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	15	120	3	4	30,00	1,18	2,5	0,85	2,139	1,6416	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
8	15	120	3	6	20,00	1,54	2,5	0,85	2,7972	2,1467	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	15	120	3	8	15,00	1,74	2,5	0,85	3,1621	2,4267	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
8	15	120	3	10	12,00	1,82	2,5	0,85	3,3058	2,537	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	4	40,00	1,21	2,5	0,85	2,2039	1,6913	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
8	20	160	3	6	26,67	1,63	2,5	0,85	2,9685	2,2781	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	20	160	3	8	20,00	1,90	2,5	0,85	3,4632	2,6678	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	10	16,00	2,05	2,5	0,85	3,7296	2,8623	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	12	13,33	2,11	2,5	0,85	3,8278	2,9376	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3	4	50,00	1,23	2,5	0,85	2,2447	1,7227	EB	6	0,8	1	0,61	0,64	0,52	12,2	15,36	20,8
8	25	200	3	6	33,33	1,69	2,5	0,85	3,0817	2,365	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
8	25	200	3	8	25,00	2,02	2,5	0,85	3,6731	2,8189	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3	10	20,00	2,22	2,5	0,85	4,0404	3,1008	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	3	12	16,67	2,33	2,5	0,85	4,2283	3,245	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	3	14	14,29	2,36	2,5	0,85	4,2853	3,2887	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	10	80	3	4	20,00	1,11	2,5	0,85	2,0202	1,5604	EB	6	0,8	1	0,63	0,64	0,52	12,6	15,36	20,8
8	10	80	3	6	13,33	1,38	2,5	0,85	2,5078	1,9246	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
8	10	80	3	8	10,00	1,48	2,5	0,85	2,6936	2,0672	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	15	120	3	4	30,00	1,18	2,5	0,85	2,139	1,6416	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
8	15	120	3	6	20,00	1,54	2,5	0,85	2,7972	2,1467	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	15	120	3	8	15,00	1,74	2,5	0,85	3,1621	2,4267	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
8	15	120	3	10	12,00	1,82	2,5	0,85	3,3058	2,537	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	4	40,00	1,21	2,5	0,85	2,2039	1,6913	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
8	20	160	3	6	26,67	1,63	2,5	0,85	2,9685	2,2781	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	20	160	3	8	20,00	1,90	2,5	0,85	3,4632	2,6678	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	10	16,00	2,05	2,5	0,85	3,7296	2,8623	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	20	160	3	12	13,33	2,11	2,5	0,85	3,8278	2,9376	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3	4	50,00	1,23	2,5	0,85	2,2447	1,7227	EB	6	0,8	1	0,61	0,64	0,52	12,2	15,36	20,8
8	25	200	3	6	33,33	1,69	2,5	0,85	3,0817	2,365	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
8	25	200	3	8	25,00	2,02	2,5	0,85	3,6731	2,8189	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3	10	20,00	2,22	2,5	0,85	4,0404	3,1008	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	3	12	16,67	2,33	2,5	0,85	4,2283	3,245	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	25	200	3	14	14,29	2,36	2,5	0,85	4,2853	3,2887	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
8	10	80	3,5	4	20,00	0,95	3	0,85	1,5504	1,2579	EB	6	0,8	1	0,68	0,72	0,6	13,6	17,28	24
8	10	80	3,5	6	13,33	1,18	3	0,85	1,9246	1,5615	EB	6	0,8	1	0,63	0,656	0,536	12,6	15,74	21,44
8	10	80	3,5	8	10,00	1,27	3	0,85	2,0672	1,6771	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
8	15	120	3,5	4	30,00	1,01	3	0,85	1,6416	1,3319	EB	6	0,8	1	0,66	0,704	0,584	13,2	16,9	23,36
8	15	120	3,5	6	20,00	1,32	3	0,85	2,1467	1,7417	EB	6	0,8	1	0,61	0,64	0,52	12,2	15,36	20,8
8	15	120	3,5	8	15,00	1,49	3	0,85	2,4267	1,9688	EB	6	0,8	1	0,59	0,64	0,52	11,8	15,36	20,8
8	15	120	3,5	10	12,00	1,56	3	0,85	2,537	2,0583	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	20	160	3,5	4	40,00	1,04	3	0,85	1,6913	1,3722	EB	6	0,8	1	0,66	0,704	0,584	13,2	16,9	23,36
8	20	160	3,5	6	26,67	1,40	3	0,85	2,2781	1,8483	EB	6	0,8	1	0,6	0,64	0,52	12	15,36	20,8
8	20	160	3,5	8	20,00	1,63	3	0,85	2,6578	2,1563	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	20	160	3,5	10	16,00	1,76	3	0,85	2,8623	2,3222	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	20	160	3,5	12	13,33	1,80	3	0,85	2,9376	2,3833	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	25	200	3,5	4	50,00	1,06	3	0,85	1,7227	1,3976	EB	6	0,8	1	0,66	0,688	0,568	13,2	16,51	22,72
8	25	200	3,5	6	33,33	1,45	3	0,85	2,365	1,9188	EB	6	0,8	1	0,59	0,64	0,52	11,8	15,36	20,8
8	25	200	3,5	8	25,00	1,73	3	0,85	2,8189	2,287	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
8	25	200	3,5	10	20,00	1,90	3	0,85	3,1008	2,5157	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3,5	12	16,67	1,99	3	0,85	3,245	2,6327	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
8	25	200	3,5	14	14,29	2,02	3	0,85	3,2887	2,6682	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6

Tab. 5 Preliminary studies assessment table (IV a) medium sized offices for different user areas.

Specific surface	Number of work places	AREA	HEIGHT	LENGTH	WIDTH	ROOM INDEX	HEIGHT OF THE LUMINARIES	TASK HEIGHT	DIRECT / INDIRECT	DIRECT	BALLAST TYPE		kA	kL	k_{RD}	k_{RDI}	K_{Ri}	DIRECT	DIRECT/INDIRECT	INDIRECT
									k	k								Pj	Pj	Pj
10	10	100	2,7	4	25,00	1,28	2,2	0,85	3,2922	1,8639	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
10	10	100	2,7	6	16,67	1,63	2,2	0,85	2,6144	2,3847	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
10	10	100	2,7	8	12,50	1,81	2,2	0,85	3,4188	2,6368	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
10	15	150	2,7	4	37,50	1,34	2,2	0,85	3,8647	1,9538	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
10	15	150	2,7	6	25,00	1,79	2,2	0,85	4,0404	2,6155	EB	6	0,8	1	0,55	0,53	0,42	11	12,72	16,8
10	15	150	2,7	8	18,75	2,08	2,2	0,85	2,6936	3,0311	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
10	15	150	2,7	10	15,00	2,22	2,2	0,85	3,6281	3,2432	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
10	20	200	2,7	4	50,00	1,37	2,2	0,85	4,2328	2,002	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
10	20	200	2,7	6	33,33	1,88	2,2	0,85	4,5594	2,7485	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
10	20	200	2,7	8	25,00	2,24	2,2	0,85	4,6784	3,276	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
10	20	200	2,7	10	20,00	2,47	2,2	0,85	2,7435	3,6036	EB	6	0,8	1	0,58	0,58	0,47	11,8	13,92	18,8
10	20	200	2,7	12	16,67	2,58	2,2	0,85	3,7665	3,7712	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
10	25	250	2,7	4	62,50	1,39	2,2	0,85	4,4893	2,0321	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
10	25	250	2,7	6	41,67	1,94	2,2	0,85	4,9383	2,835	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
10	25	250	2,7	8	31,25	2,36	2,2	0,85	5,168	3,4429	EB	6	0,8	1	0,53	0,53	0,39	10,6	12,72	15,6
10	25	250	2,7	10	25,00	2,65	2,2	0,85	5,2376	3,861	EB	6	0,8	1	0,53	0,53	0,39	10,6	12,72	15,6
10	25	250	2,7	12	20,83	2,82	2,2	0,85	2,0202	4,1158	EB	6	0,8	1	0,63	0,64	0,52	12,6	15,36	20,8
10	25	250	2,7	14	17,96	2,91	2,2	0,85	2,5078	4,2419	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
12	10	120	3	4	30,00	1,18	2,5	0,85	2,6936	1,6416	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
12	10	120	3	6	20,00	1,54	2,5	0,85	2,139	2,1467	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
12	10	120	3	8	15,00	1,74	2,5	0,85	2,7972	2,4267	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
12	10	120	3	10	12,00	1,82	2,5	0,85	3,1621	2,537	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
12	15	180	3	4	45,00	1,22	2,5	0,85	3,3058	1,7086	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
12	15	180	3	6	30,00	1,67	2,5	0,85	2,2039	2,3256	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
12	15	180	3	8	22,50	1,97	2,5	0,85	2,9685	2,7449	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
12	15	180	3	10	18,00	2,14	2,5	0,85	3,4632	2,99	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
12	15	180	3	12	15,00	2,22	2,5	0,85	3,7296	3,1008	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
12	20	240	3	4	60,00	1,25	2,5	0,85	3,8278	1,7442	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
12	20	240	3	6	40,00	1,74	2,5	0,85	2,2447	2,4267	EB	6	0,8	1	0,61	0,64	0,52	12,2	15,36	20,8
12	20	240	3	8	30,00	2,11	2,5	0,85	3,0817	2,9376	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6
12	20	240	3	10	24,00	2,35	2,5	0,85	3,6731	3,2832	EB	6	0,8	1	0,55	0,56	0,44	11	13,44	17,6
12	20	240	3	12	20,00	2,50	2,5	0,85	4,0404	3,4884	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
12	20	240	3	14	17,14	2,57	2,5	0,85	4,2283	3,5844	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
12	25	300	3	4	75,00	1,27	2,5	0,85	4,2853	1,7663	EB	6	0,8	1	0,53	0,53	0,42	10,6	12,72	16,8
12	25	300	3	6	50,00	1,79	2,5	0,85	2,0202	2,4917	EB	6	0,8	1	0,63	0,64	0,52	12,6	15,36	20,8
12	25	300	3	8	37,50	2,20	2,5	0,85	2,5078	3,0667	EB	6	0,8	1	0,59	0,58	0,47	11,8	13,92	18,8
12	25	300	3	10	30,00	2,50	2,5	0,85	2,6936	3,4884	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
12	25	300	3	12	25,00	2,70	2,5	0,85	2,139	3,7712	EB	6	0,8	1	0,62	0,64	0,52	12,4	15,36	20,8
12	25	300	3	14	21,43	2,82	2,5	0,85	2,7972	3,9385	EB	6	0,8	1	0,58	0,58	0,47	11,6	13,92	18,8
12	25	300	3	16	18,75	2,88	2,5	0,85	3,1621	4,0154	EB	6	0,8	1	0,58	0,56	0,44	11,6	13,44	17,6

Tab. 6 Preliminary studies assessment table (IV b) medium sized offices for different user areas.

8.2. Refined case studies

As following step it has been decided to investigate more accurately the assessment of three of the preliminary case studies. These three particular cases have been defined according to a real application. According to the three simulations on this refined case studies it has been decided which of those should be to realized.

Parameter		Case studies		
		Case A	Case B	Case C
Width			11,6	
Length			8,5	
Height			2,7	
Total Area			98,6	
		Length	*Width*	*Area*
Surface 1	Work area	8,6	7,5	64,5
Surface 2	Meeting room	3	6	18
Surface 3	Corridor	8,6	1,1	9,46
Surface 4	Corridor	3	1,8	5,4
Surface 5	Wall 1	7,4	0,12	0,888
Surface 6	Wall 2 (included door)	3	0,12	0,36
Total Area			98,6	
Facade	*Orientation*		Nord	
	Obstruction		No	
	Light transmission ratio t_{D65}		0,74	
	Fenestration Correction factor k_1		0,7	
	Frame Correction factori k_2		0,9	
	Fenestration Ratio		40%	
Lighting system	*Lampen*		Linear Fluorescent / Compact Fluorescent	
	Ballast		EVG	
	Type of installation	Direct	Direct / Diffused	Direct / Diffused
	Lighting strategy	Room related	Room related	Room related
	Room index		1,82	
	Specific installed power		According to case study type	
	Maintained illuminance: work area		500 lux	
	Maintained illuminance: meeting room		500 lux	
	Maintained illuminance: corridors		200 lux	
	Presence control	No	Yes	Yes
	Daylight control	Manual	Automatic	Automatic

Figure 8-4 Case studies schedule

In Figure 8-4 are represented the three cases. The fenestration height is 1,2 m. The layout is the same for all the cases and is referred to a real office. This office is divided in 4 zones; the first one is the work zone with 8 work places. Each user has 8 m^2 available and the surface of this zone is 64 m^2. The second zone is used as meeting room and measures 18 m^2. The third and fourth zone are corridors and pace 14,86 m^2.

The room surfaces have the following optic properties:

- Ceiling : 0,8

- Walls: 0,7

- Working planes: 0,5

- Floor: 0,5

The aim is to obtain in the work zone a maintained illuminate on the task area of 500 lux and 300 lux on the surrounding area according to the standard prescriptions. In the corridors the lower allowed limit of the average maintained illuminance should be 200 lux. This value is higher according to the standard in

force nonetheless it has seemed to be a reasonable value according to the architectonical characteristics of the spaces. (Figure 8-6). Work zone and corridors are matter of facts only virtually divided and a too lower value of the average maintained illuminate in corridors hasn't allowed reaching a good uniformity between the two zones. In each case it has been assumed to use luminaires with linear fluorescent lamps or compact fluorescent lamps according to the case variation. All the luminaires are fed through electronic ballast. The first comparison that has been made was to compare the installed power per m^2 calculated with the tabular method of the DIN 18599-4 and to compare it with the benchmark values of the EN standard (Figure 8-5).

	Qual. class	Parasitic Emergency kWh/(m²/year)	Parasitic Control kWh/(m²/year)	PN W/m²
Office	*	1	5	15
	**	1	5	20
	***	1	5	25

Figure 8-5 EN15193 Benchmarks values for the specific installed power

The first difficulty is that the DIN method doesn't allow estimating contemporary more zones with more luminaires' type. The meeting room, for instance, is supplied in the case variation B (see 8.3.2) by direct/indirect luminaires with linear fluorescent lamps and by direct luminaires with fluorescent compact lamps. We made the assumption where required that that the different zones with different illumination types could be supplied partially by the first illumination type and partially by the second illumination type. The obtained results are reported in Figure 8-5 a show no stronger deviation with the following simulations.

Figure 8-6 Office layout

Figure 8-7 Calculation table for the specific installed power through the "corrected" DIN method

Parameter	CASE A — WORK ROOM	CASE A — MEETING ROOM	CASE A — CORRIDOR 1	CASE A — CORRIDOR 2	CASE B — WORK ROOM	CASE B — MEETING ROOM	CASE B — CORRIDOR 1	CASE B — CORRIDOR 2	CASE C — WORK ROOM	CASE C — MEETING ROOM	CASE C — CORRIDOR 1	CASE C — CORRIDOR 2
Specific surface	8	6			8.1	6			8.1	7.2		
Number of work places	8	3			8	3			8	2.5		
AREA	65	18	5.4	9.5	65	18	5.4	9.5	65	18	5.4	9.5
HEIGHT	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
LENGTH	7.5	3	3	8.6	7.5	3	3	8.6	7.5	3	3	8.6
WIDTH	8.60	6.00	1.80	1.10	8.60	6.00	1.80	1.10	8.60	6.00	1.80	1.10
ROOM INDEX	1.43	0.71	0.40	0.35	1.43	0.71	0.40	0.35	1.43	0.71	0.40	0.35
HEIGHT OF THE LUMINARIES	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.40	2.40	2.70	2.70
TASK HEIGHT	0.85	0.85	0	0	0.85	0.85	0	0	0.85	0.85	0	0
κ DIRECT / INDIRECT	2.054	1.026	0.402	0.348	2.054	1.026	0.402	0.348	2.585	1.290	0.417	0.361
κ DIRECT	2.054	1.026	0.402	0.348	2.054	1.026	0.402	0.348	2.054	1.026	0.402	0.348
BALLAST TYPE	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB
k_A	6	6	3	3	6	6	3	3	6	6	3	3
k_L	0.80	0.90	1.00	1.00	0.80	0.90	1.00	1.00	0.80	0.90	1.00	1.00
k_{RD}	0.580	0.770	1.080	1.080	0.580	0.770	1.080	1.080	0.580	0.770	1.080	1.080
$k_{RD/I}$	0.640	0.900	1.300	1.300	0.640	0.900	1.300	1.300	0.580	0.790	1.300	1.300
Pj DIRECT	11.6	15.6	13.0	13.0	11.6	9.7	13.0	13.0		8.3	13.0	13.0
Pj DIRECT/INDIRECT	24.3				17.7				21.9	17.7		
Average specific installed	12.55				15.94				19.26			

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DIRECT vs DIRECT/INDIRECT LIGHTING
CASE a

Figure 8-8 Specific installed power for CASE A subdivided between direct and indirect lighting.

DIRECT vs DIRECT/INDIRECT LIGHTING
CASE B
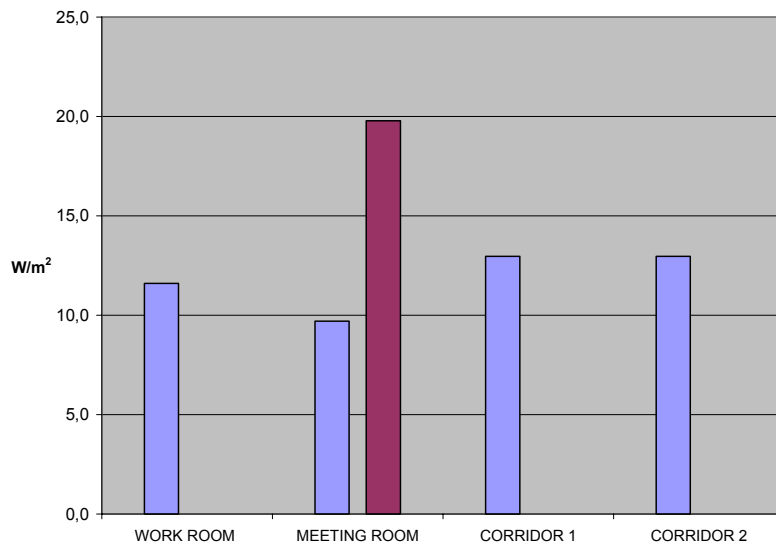
Figure 8-9 Specific installed power for CASE B subdivided between direct and indirect lighting.
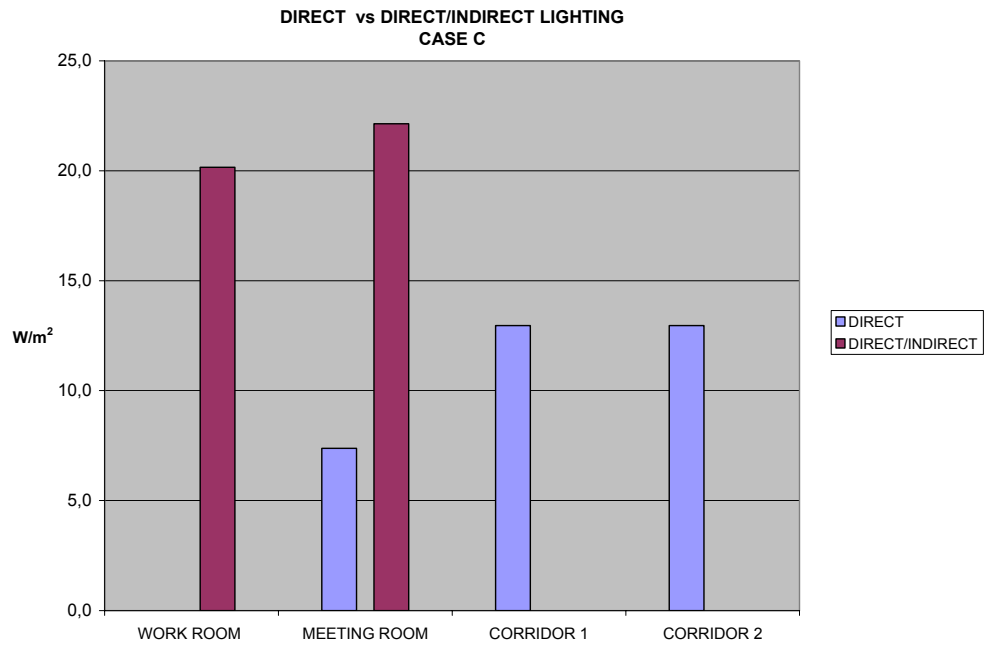
Figure 8-10 Specific installed power for CASE C subdivided between direct and indirect lighting.
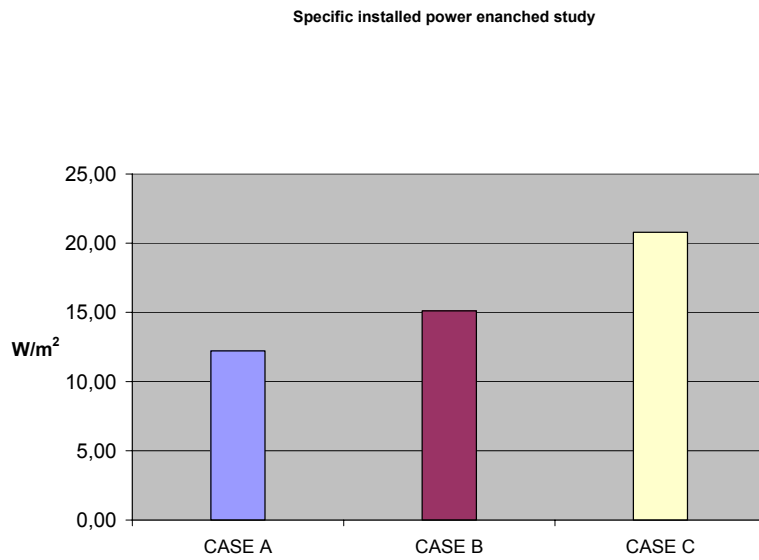
Figure 8-11 Comparison between the three cases

8.2.1. Lighting management systems of the case studies

Two different case studies have been taken in consideration:

- Manual without constant illuminance system (Traditional system)

- Automatic with presence sensor and constant illuminance system driven by a DALI management system

8.2.1.1 _Traditional system_

In this system we made the assumption to install luminaires' controller manually. Different switching groups have been planned. Those groups drive the luminaires over different takes areas or corridors. It has not been assumed in this system to use constant illuminance system driven by a daylight sensor. The luminaires are not dimmerable with the exception of the meeting room. No BUS system has been chosen.

8.2.1.2 _DALI system_

The second lighting management system is a DALI system with presence control and with constant illuminance system. This solution allows a flexible control of the switching points that is always programmable according to the user's needs. Every luminary is manageable independently and different lighting scenarios can be chosen. All the luminaires switch off without user's presence and dim automatically according to the information coming from the daylight sensor.

8.2.2.   **Metering**

The Energy consumption metering system has been planned according to the EN 15193 requirements. The lighting consumption con measured through a lighting management system that logs the hour run, the proportionality (dimming level) and relates this to its data base on installed load. Moreover two separate digital energy meters has been installed on the power circuit and on the lighting circuits.
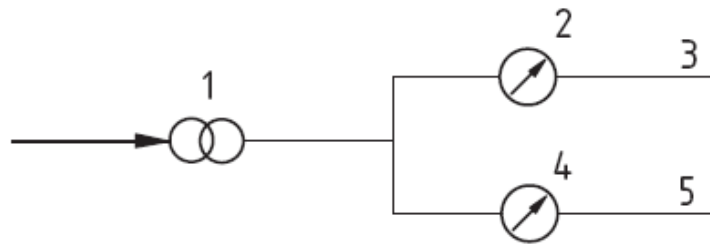
Key

1. Primary power   4. kWh lighting meter
2. kWh meter other circuits   5. Lighting circuit
3. Power circuit
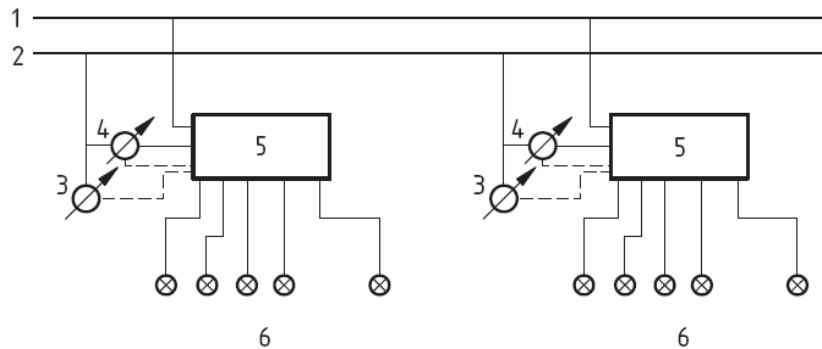
Key

1. Bus line   4. Ampere meter
2. 230 volt power   5. Light controller
3. Volt meter   6. Luminaires

Figure 8-12 Metering circuits

8.3. Simulation of the three case studies

The three case studies are planned to represent the requirements of the three lighting quality classes describe in the European standard EN15193 (Figure 8-13). According to the EN 15193 lighting should be designed and installed by following good lighting practices. The lighting design criteria for offices are given in the EN 12464-1. The lighting solution should fulfill the basic lighting requirements. For an improved lighting design, to achieve better comfort conditions, well being of and acceptance by the user the following three lighting classes should be considered.

- Basic fulfillment of requirements (class $*$)

- Good fulfillment of requirements (class $**$)

- Comprehensive fulfillment of the requirements (class $***$)

	Lighting design criteria class		
	$*$	$**$	$***$
Maintained illuminance on horizontal visual tasks ($E_{M\,horizontal}$)	☑	☑	☑
Appropriate control of discomfort glare (UGR)	☑	☑	☑
Avoidance of flicker and stroboscopic effects	✓	✓	✓
Appropriate control of veiling reflections and reflected glare		✓	✓
Improved colour rendering		☑	☑
Avoidance of harsh shadows or too diffuse light in order to provide good modelling		✓	✓
Proper luminance distribution in the room ($E_{vertical}$)		✓	✓
Special attention of visual communication in lighting faces ($E_{cylindrical}$)			✓
Special attention to health issues (Note)			✓

☑: has to comply with required values from Tables 5.3 in EN 12464-1

✓: has to conform to verbally described requirements from EN 12464-1

NOTE health issues may even require much higher illuminances and therefore higher W/m^2

The maximum power density load (PN) connected to the lighting design class is given in the benchmark Table F.1.

Figure 8-13 Table F2 EN 15193 Lighting design criteria class

8.3.1.   **CASE A**

The Case A is defined by the following characteristics and represents a solution that is rated, in the EN 15193, as one star lighting quality class. (Class ∗).

- In ceiling luminaires with electronic ballast

- Direct lighting for the whole office.

- No presence control

- Manual switching of lights

- No constant lighting control (daylight control)

8.3.1.1   *Peculiar characteristics of CASE A*

In this solution it has been chosen to foresee square elements (600 mm X 600 mm) plaster ceiling with a free height of 2,7 m. The luminaires are in-ceiling type. The reflection coefficients are the same for all the case studies and are the ones reported in paragraph 8.2. There is no need of BUS lines for the management of the luminaires switching and the user will switch them manually.

The luminaires are divided into 3 switching groups for both corridors and work area and a group for the meeting room. Only the meeting room group can be manually dimmed.
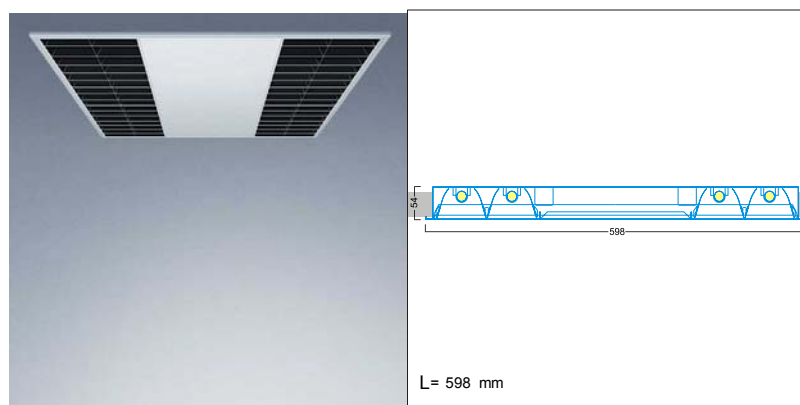
Figure 8-14 In-ceiling dark light optic luminaires 4X14W T5 with electronic ballast.
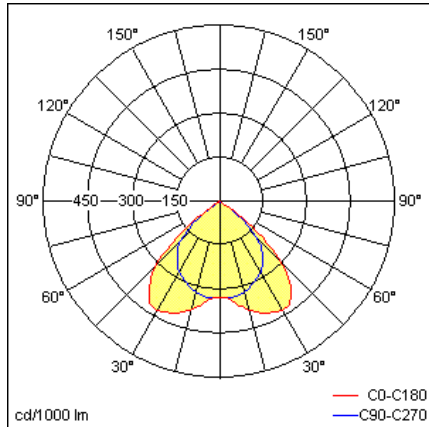
Figure 8-15 Photometric curve of the dark light luminaires

The predicted maintained illuminance is 500 lux and the glare control assessment give as results that UGR level are under <19 with a $L_{65°}$ inferior to $1000cd/m^2$.

The in ceiling luminaires give an appreciable architectonic effect and reduce effectively the energetic consumption due to the usage of the state of the art T5 lamps driven by electronic ballast.
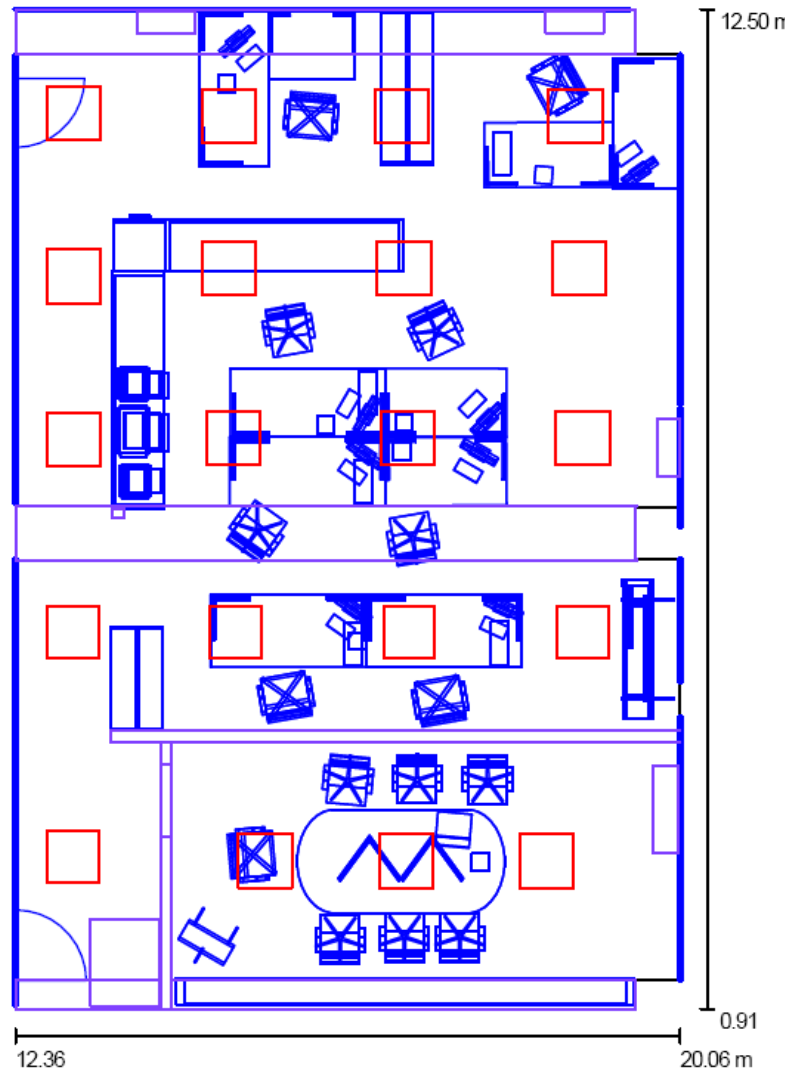
Figure 8-16 Luminaires lay-out

This solution present a specific installed power of 11.08W/m² that means 1.78 W/m² for every 100 lx on a floor a net area of 88.49 m²

Figure 8-17 to Figure 8-20 show the more important calculated values that should be taken in consideration for the different task areas. The average maintained illuminance calculated is 642 lux and the lower illuminance on the task 1 is 310 lux. The ration between the two values gives us the uniformity ratio that could be interpreted as to low according to the standard requirements of the EN 12464-1. To this point we have to say that the lower value reached on the task area 1

depends that the task area confines with the wall whose influence doesn't allow reaching better values. According to that we have to say that the simulation was made with the office completely furnished with pc stations and monitors. The position of the PC monitor inside the task area causes a lower value punctually. Under this consideration this peculiar situation seems to be acceptable. The Average illuminance on the surrounding areas has uniformity higher than the reference values required by the EN 12464-1

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 1	64 x 64	642	310	788	0.48	0.39
	Area circostante 1	128 x 128	700	531	793	0.76	0.67

Figure 8-17 Uniformity in the Task area 1

The task area 2 satisfies completely the standard requirements.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 2	64 x 64	629	499	779	0.79	0.64
	Area circostante 2	128 x 128	624	440	783	0.70	0.56

Figure 8-18 Uniformity in the Task area 2

For the task area 3 the same consideration of the task area 1 can be done. All in all the situation presents only a punctual deviation from the prescribed uniformity levels that is even weaker than in task area 1.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 3	128 x 128	647	418	728	0.65	0.57
	Area circostante 3	128 x 128	660	578	724	0.88	0.80

Figure 8-19 Uniformity in the Task area 3

The task area 4 satisfies completely the standard requirements.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 4	100 x 100	683	508	789	0.74	0.64
	Area circostante 4	128 x 128	644	424	788	0.66	0.54

Figure 8-20 Uniformity in the Task area 4
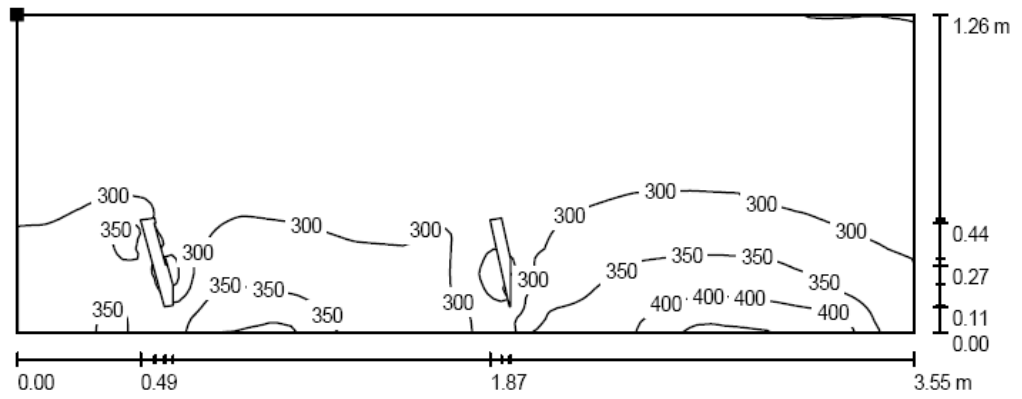
Reticolo: 8 x 16 Punti

E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
372	302	417	0.81	0.72

Figure 8-21 Vertical illuminance on the task area 3
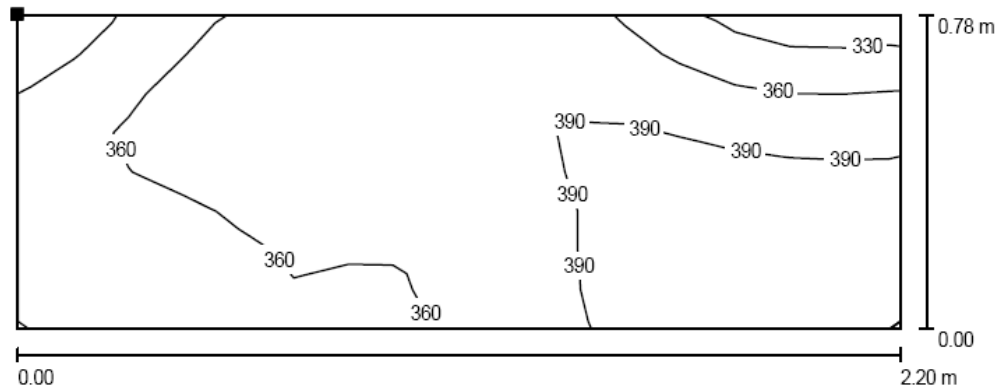
Reticolo: 64 x 128 Punti

E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
297	219	468	0.74	0.47

Figure 8-22 Vertical illuminance on the task area 2

Figure 8-23 Iso-illuminance curves distribution: 400 lx red, 500 lx brown and 600 lx yellow.

All the task area respect the requirements of the UGR limitation according to the EN 12464-1, the limit value for computer work is under 19. The higher reached value is 18.5 on the task area 3. Our results shows that on the task areas we have, with exception of one case, a value near 16 that is only few decimals higher than the requested limit for the task "technical drawing". This kind of task has to be considered as the task with the strictest requirements. However this kind of activity has not to be taken in consideration as a possible task for the user of the office.

Lista superfici UGR

No.	Denominazione	Posizione [m]			Dimensioni [m]		Linea di mira [°]
		X	Y	Z	L	P	
1	Superficie di calcolo UGR 1	15.326	11.265	1.200	1.834	1.686	0.0
2	Superficie di calcolo UGR 2	18.545	11.115	1.200	1.674	1.674	0.0
3	Superficie di calcolo UGR 3	16.484	7.641	1.200	3.943	3.361	0.0
4	Superficie di calcolo UGR4	16.413	5.143	1.200	4.038	1.680	0.0

Figure 8-24 UGR value on the investigated surfaces
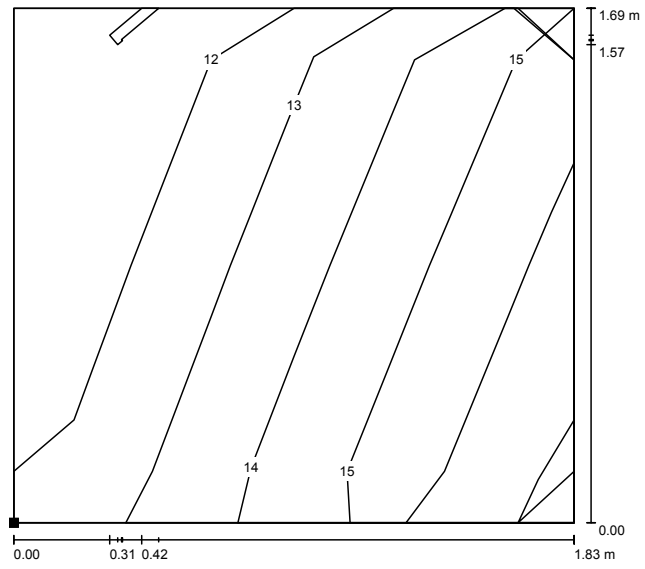
Figure 8-25 UGR value on task area 1
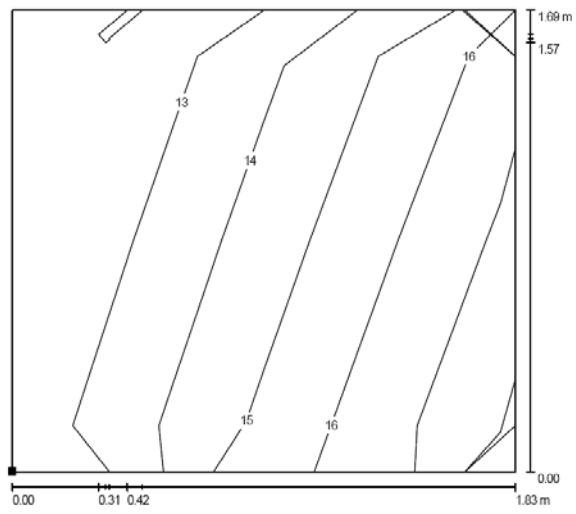
Figure 8-26 UGR value on task area 2
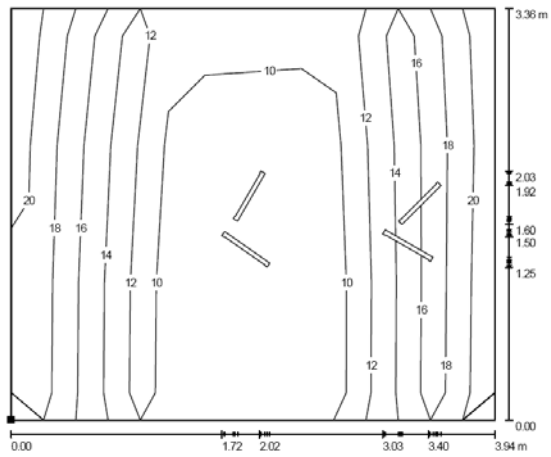
Figure 8-27 UGR value on task area 3
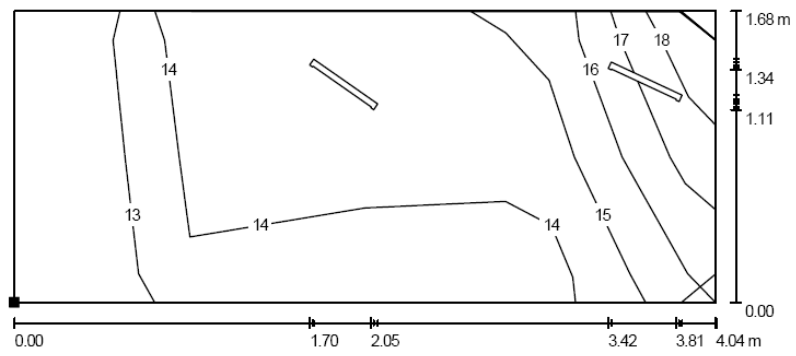
Figure 8-28 UGR value on task area 4
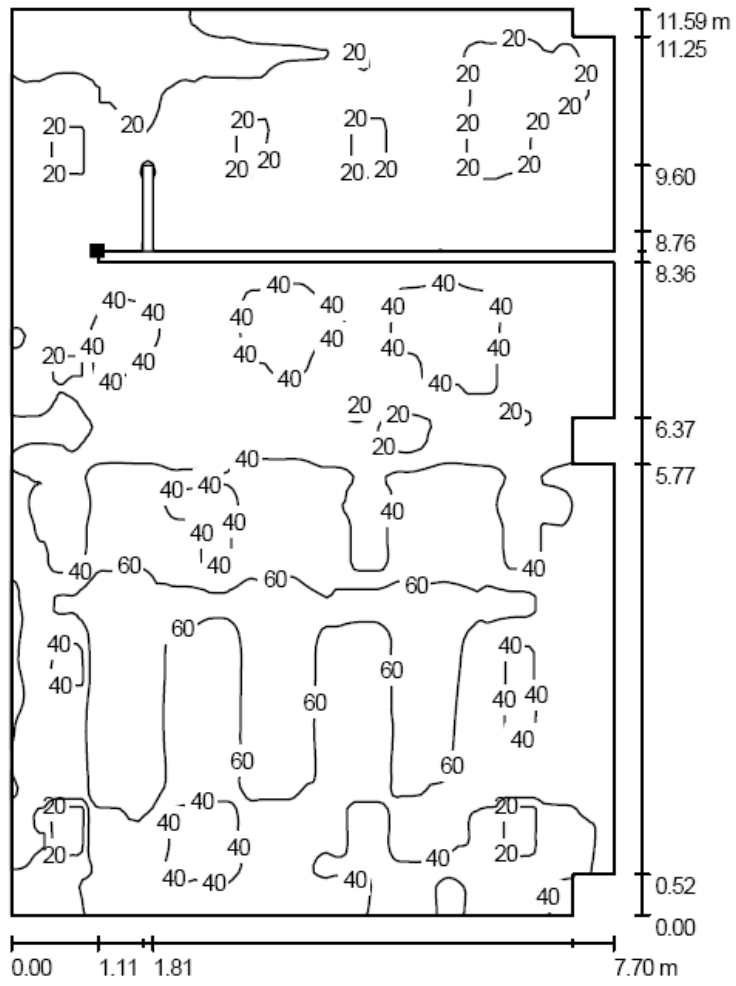
Figure 8-29 Luminance distribution on the ceiling cd/m²
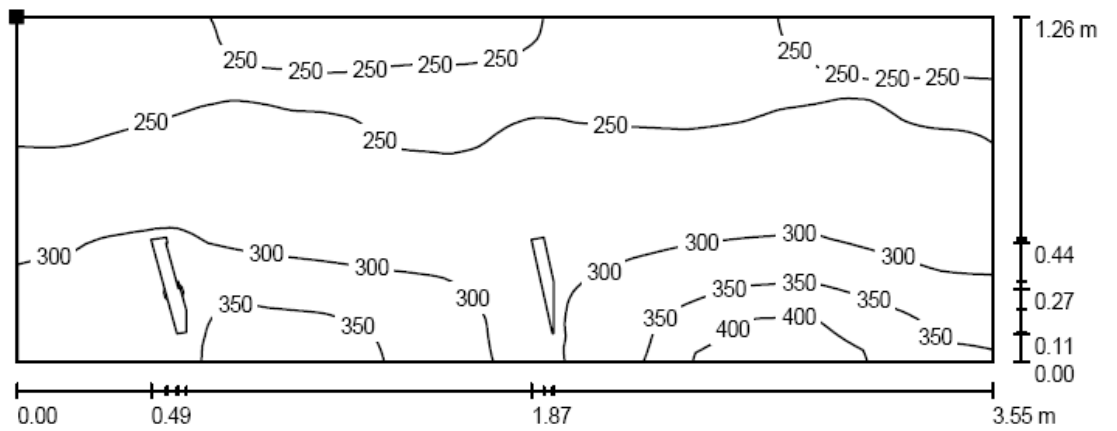
Figure 8-30 Vertical illuminance value on the task area 1

224
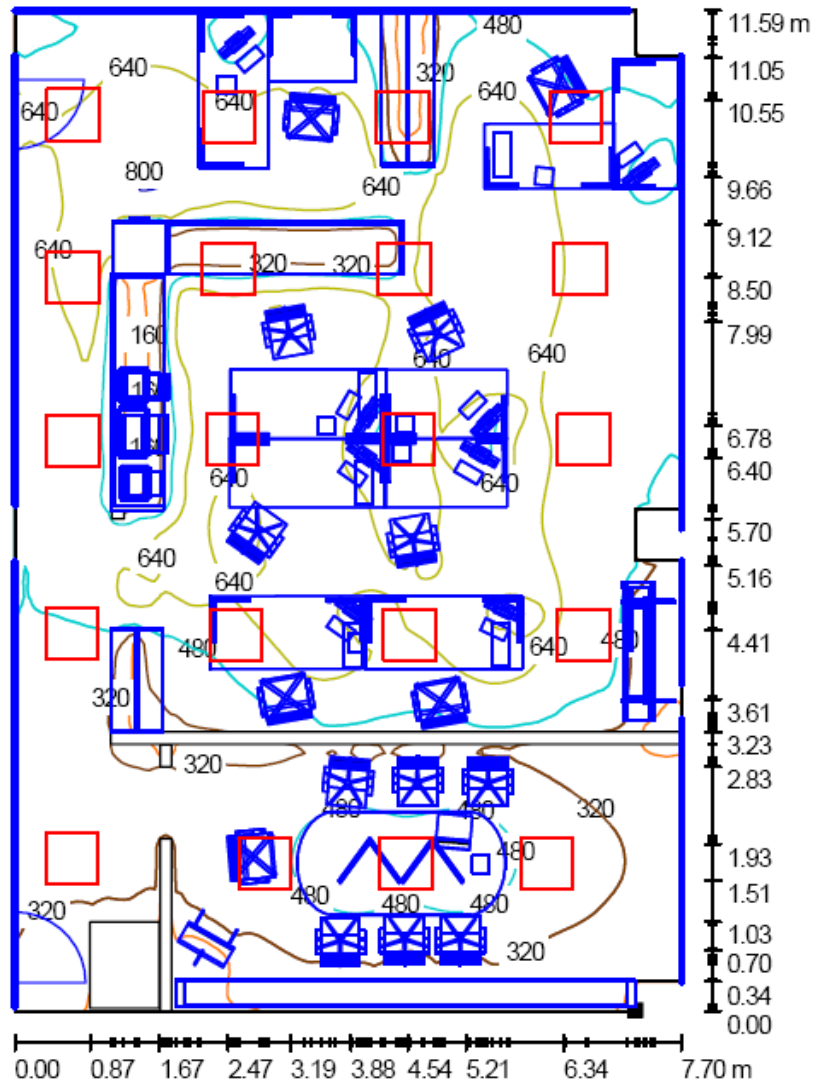
Figure 8-31 Illuminance Isolinee distribution
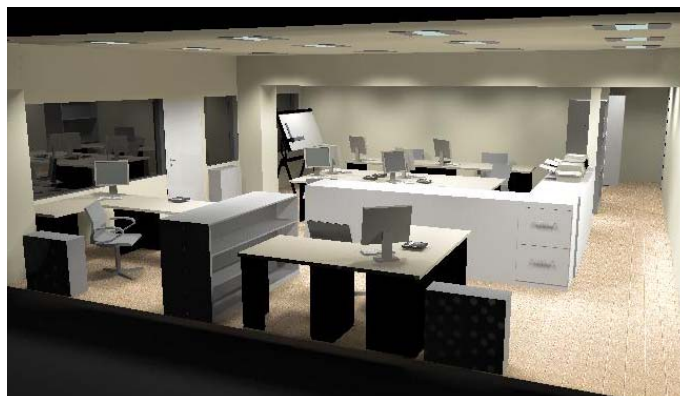
Figure 8-32 Rendering of the working area

Figure 8-33 Rendering of the working area
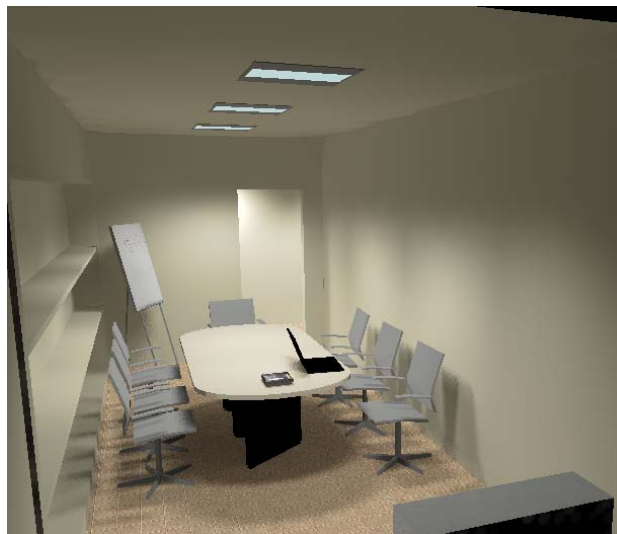
Figure 8-34 Rendering of the meeting room

Total energy consumtion for the lighting system:	2018,23

Energy consumption for the visual task	1499,47	kWh/year
Parasitic energy consumption for standby	86,46	kWh/year
Parasitic energy consumption for emergency lighting	432,30	kWh/year
Total energy consumption	2018,23	kWh/year
Surface	86,46	m^2
LENI	23,34	kWh/year

Month	Lighting		Visual task		Parasitic + Emerg.	
	kWh	[kWh/m²]	kWh	[kWh/m²]	kWh	[kWh/m²]
Gen	199,24	2,3	156,01	1,8	43,23	0,5
Feb	196,94	2,28	153,71	1,78	43,23	0,5
Mar	195,05	2,26	151,82	1,76	43,23	0,5
Apr	194,63	2,25	151,4	1,75	43,23	0,5
Mag	194,32	2,25	151,09	1,75	43,23	0,5
Giu	194,43	2,25	151,2	1,75	43,23	0,5
Lug	194,32	2,25	151,09	1,75	43,23	0,5
Ago	194,32	2,25	151,09	1,75	43,23	0,5
Set	195,05	2,26	151,82	1,76	43,23	0,5
Ott	196,31	2,27	153,08	1,77	43,23	0,5
Nov	198,61	2,3	155,38	1,8	43,23	0,5
Dic	199,97	2,31	156,74	1,81	43,23	0,5
Total year	2353,19	27,23	1834,43	21,23	518,76	6

Figure 8-35 Energy consumption assessment of the CASE A

Considering the obtained values can be pointed out that the energetic consumption for square meter is relatively low. The calculated value is 21,23 kWh/m^{2}year. This solution satisfies completely the target of the lighting planning according to the EN 12464-1. Moreover it has been accomplished the goal to fulfill the requirements described in the EN 15193 for the solution of lighting quality class "one star". If we sum to the obtained values the parasitic energy consumption and the emergency lighting consumption we obtain that we have a total energy consumption value of 27,23 kWh/m^{2}year. We took in consideration 1 kWh/m^{2}anno for the parasitic Energy consumption and 5 kWh/m^{2}anno for the emergency lighting consumption as suggested from the EN standard.

The outcoming calculated value is far lower than the benchmark value suggested from the EN standard (42.1 kWh/m^{2}anno) and shown in Figure 5-20.

8.3.1.3 *CASE A-bis*

With the aim to ease the comparison between the different cases and to point out the influence a management system on the energy consumption the case A was

investigated also supposing to drive the same luminaires of the basic case with a DALI system with presence control and constant illumination control (daylight sensor). The artificial lighting results are of course the same of the basic case. The energetic results are remarkably different because the lighting energy consumption has been reduced drastically from 22,34 kWh/m^{2}year to 18,61 kWh/m^{2}year. This value is by far lower in comparison to the respective benchmark limiting value of the EN standard (32 ,2 kWh/m^{2}year) as shown in Figure 5-20.

Total energy consumtion for the lighting system:	1624,91

Energy consumption for the visual task	1106,15	kWh/year
Parasitic energy consumption for standby	86,46	kWh/year
Parasitic energy consumption for emergency lighting	432,30	kWh/year
Total energy consumption	1624,91	kWh/year
Surface	86,46	m^2
LENI	18,79	kWh/year

Month	Lighting		Visual task		Parasitic + Emerg.	
	kWh	[kWh/m²]	kWh	[kWh/m²]	kWh	[kWh/m²]
Gen	139,83	1,62	96,6	1,12	43,23	0,5
Feb	136,59	1,58	93,36	1,08	43,23	0,5
Mar	133,94	1,55	90,71	1,05	43,23	0,5
Apr	133,35	1,54	90,12	1,04	43,23	0,5
Mag	132,9	1,54	89,67	1,04	43,23	0,5
Giu	133,05	1,54	89,82	1,04	43,23	0,5
Lug	132,9	1,54	89,67	1,04	43,23	0,5
Ago	132,9	1,54	89,67	1,04	43,23	0,5
Set	133,94	1,55	90,71	1,05	43,23	0,5
Ott	135,7	1,57	92,47	1,07	43,23	0,5
Nov	138,95	1,61	95,72	1,11	43,23	0,5
Dic	140,86	1,63	97,63	1,13	43,23	0,5
Total year	1624,91	18,81	1106,15	12,81	518,76	6

Figure 8-36 Energy consumption assessment of the CASE A-BIS

8.3.2.   **CASE B**

The Case A is defined by the following characteristics and represents a solution that is rated, in the EN 15193, as two stars lighting quality class. (Class ∗∗).

• In-ceiling DALI luminaires with electronic ballast

• Direct lighting trough mellow light recessed luminaire with slotted sheet steel diffuser optic.

• Direct local lighting trough recessed highly specular downlight with faceted reflector unit made of high-quality UV-resistant polycarbonate.

- Direct/indirect lighting trough up/downlight pendant luminaire plus four recessed highly specular downlight with faceted reflector unit made of high-quality UV-resistant polycarbonate for the meeting room.

- Presence control

- Constant illuminance system (daylight sensor)

- User oriented scenarios.

- Independent group or single management of the luminaires

8.3.2.1 *Peculiar characteristics of CASE B*

Also in this solution it has been chosen to foresee square elements (600mmX600mm) plaster ceiling with a free height of 2,7 m. The luminaires are in-ceiling type with the exception of one pendant luminaire in the meeting room. The reflection coefficients are the same for all the case studies and are the ones reported in paragraph 8.2. A DALI BUS system has been used for the management of the luminaires switching and the user can switch selecting between different scenarios.

The luminaires are divided into 2 switching groups for the corridors and 3 for the work area and three groups for the meeting room.

Mellow soft lighting next to the direct lighting improves the cylindrical illuminance, a better uniformity through the use of a higher number of luminaires. Energy efficiency is improved mainly through direct lighting with T5 lamps and h.f. electronic ballast, low installed load values are reached and there is a large influence of the daylight-controlled lighting in the energy saving in comparison to CASE A (without daylight control).
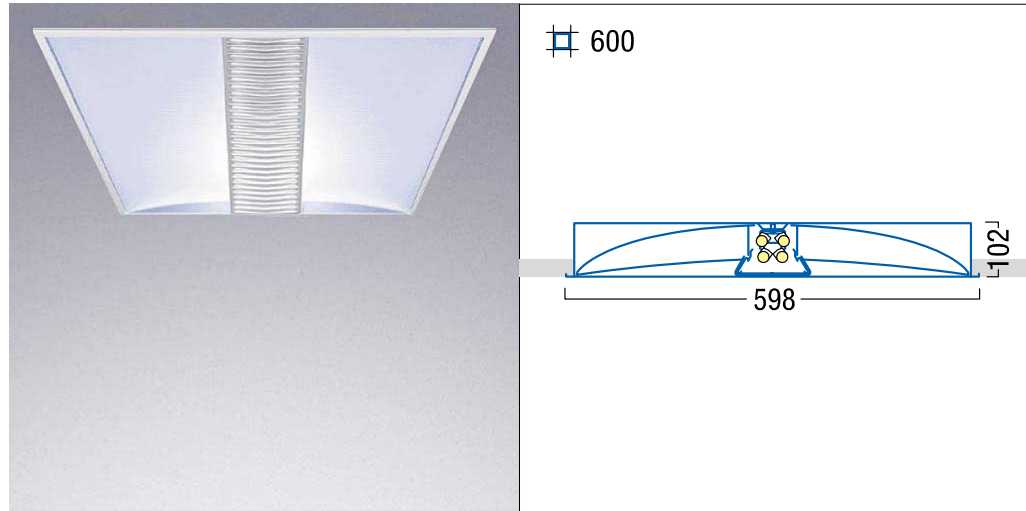
Figure 8-37 Dimmable Recessed luminaire mellow light 2X24W+2X24W T5 with electronic ballast and DALI interface
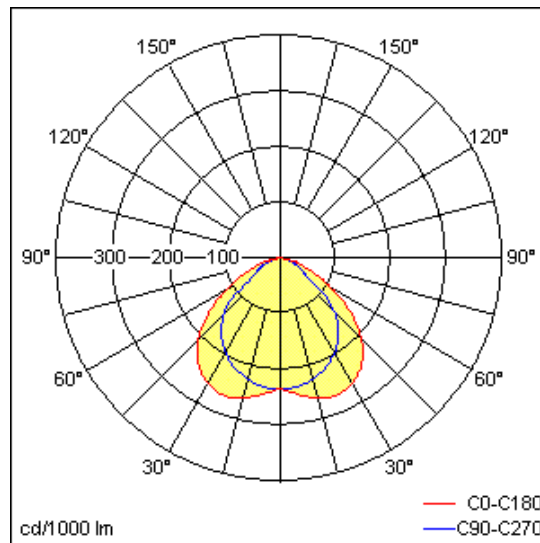
Figure 8-38 Photometric curves of the recessed mellow light luminaires
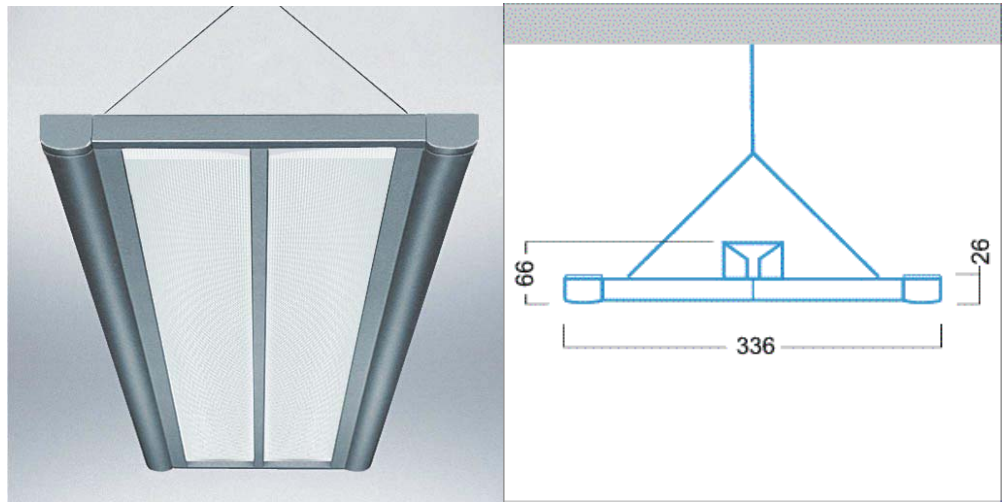
Figure 8-39 Indirect/direct waveguide luminaire 2 x 80W, for T16, with digitally addressable, dimmerable DALI electronic ballast
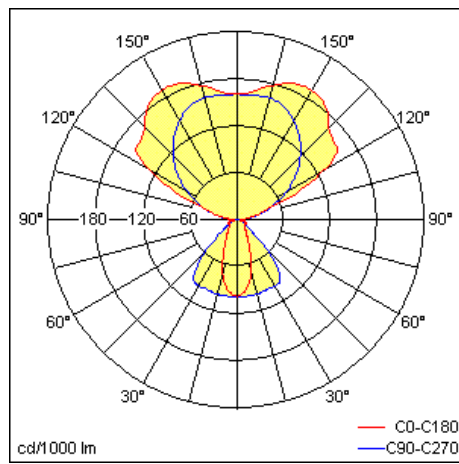
Figure 8-40 Photometric curves of the pendant direct/diffuse luminaire
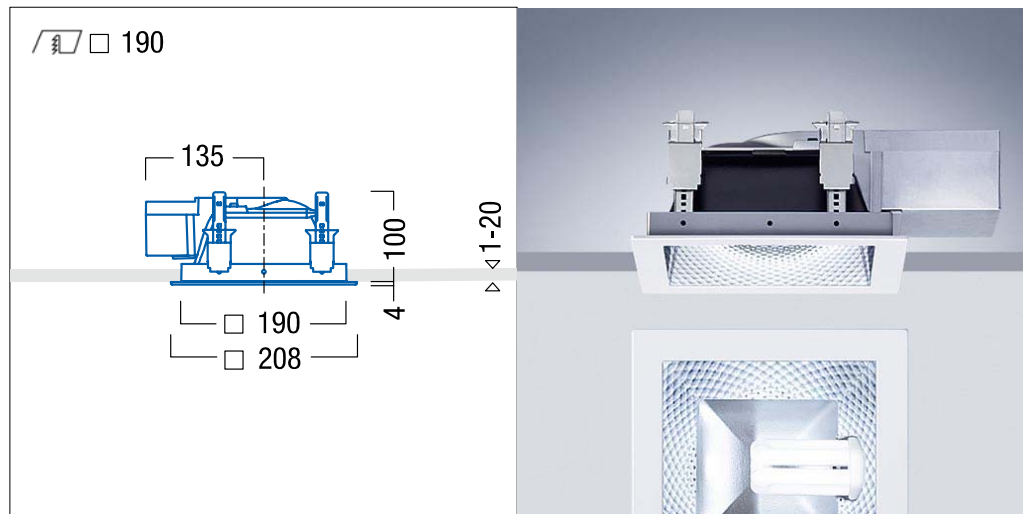
Figure 8-41 In Ceiling downlights with faceted reflector and suspended decorative glass. Compact Fluorescent lamps electronic ballast and DALI interface.
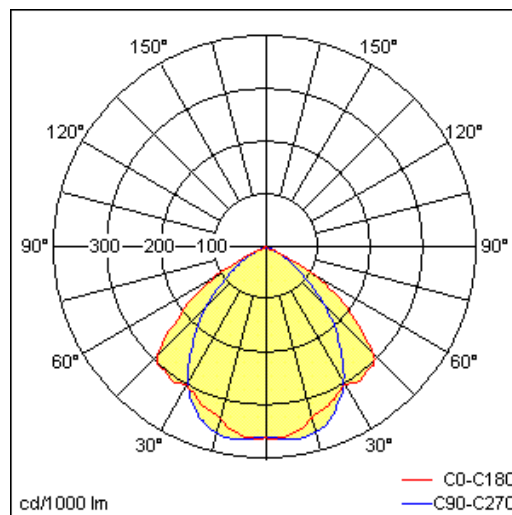
Figure 8-42 Photometric curves of the downlight luminaires

The predicted maintained illuminance is 500 lux and the glare control assessment give as results that UGR level are under <19 with a $L_{65°}$ inferior to 1000cd/m^2.

The in ceiling luminaires give an appreciable architectonic effect and reduce effectively the energetic consumption due to the usage of the state of the art T5 lamps driven by electronic ballast.

12.50 m

0.91

12.36

20.06 m
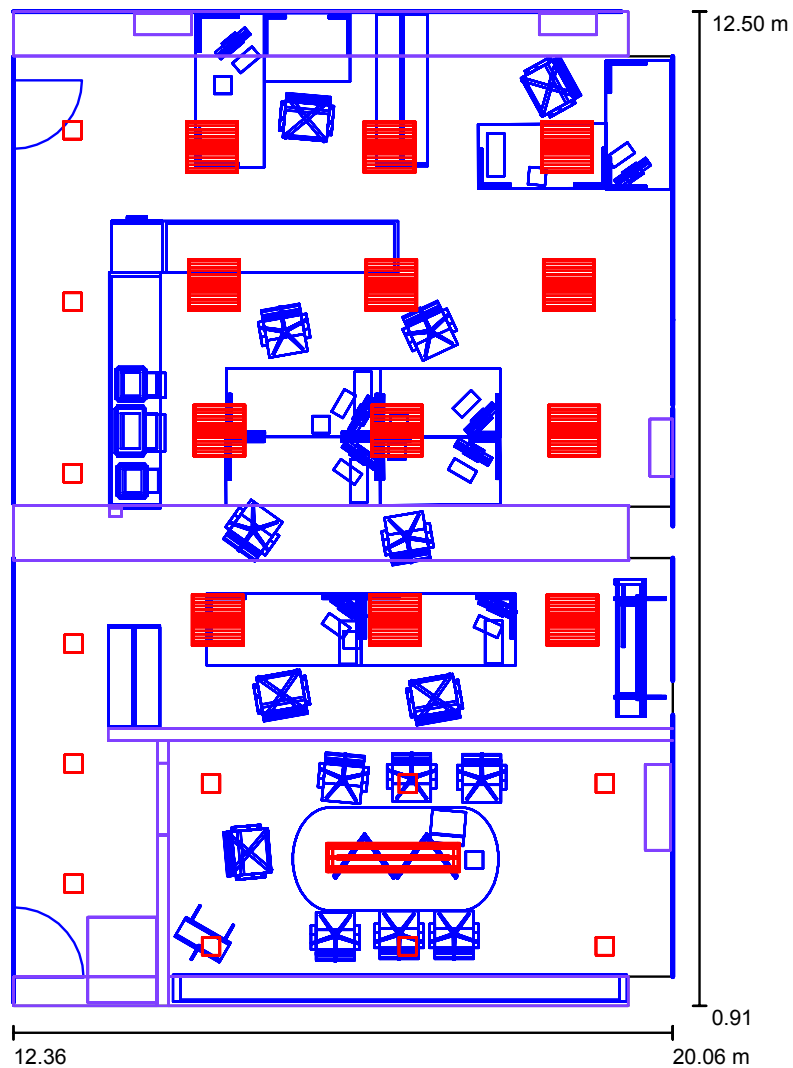
Figure 8-43 Luminaires lay-out

This solution present a specific installed power of 14.52 W/m² that means 2.65 W/m²/ for every 100 lx on a floor a net area of 88.49 m²

Figure 8-44 to Figure 8-47 show the most important calculated values that should be taken in consideration for the different task areas. The average maintained illuminance calculated is 561 lux and the lower illuminance on the task 1 is 296 lux. The ration between the two values gives us the uniformity ratio that could be interpreted as to low according to the standard requirements of the EN 12464-1. To this point we have to say that the lower value reached on the task area 1 depends that the task area confines with the wall whose influence doesn't allow

reaching better values. According to that we have to say that the simulation was made with the office completely furnished with pc stations and monitors. The position of the pc monitor inside the task area causes a lower value punctually. Under this consideration this peculiar situation seems to be acceptable. The Average illuminance on the surrounding areas has uniformity higher than the reference values required by the EN 12464-1

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 1	64 x 64	561	296	755	0.53	0.39
	Area circostante 1	128 x 128	587	393	776	0.67	0.51

Figure 8-44 Uniformity in the Task area 1

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 2	64 x 64	575	428	674	0.74	0.64
	Area circostante 2	128 x 128	529	380	695	0.72	0.55

Figure 8-45 Uniformity in the Task area 2

The task area 2 satisfies completely the standard requirements.

For the task area 3 the same consideration of the task area 1 can be done. All in all the situation presents only a punctual deviation from the prescribed uniformity levels that is even weaker than in task area 1.

The task area 4 satisfies completely the standard requirements.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 3	128 x 128	620	418	734	0.67	0.57
	Area circostante 3	128 x 128	625	516	772	0.83	0.67

Figure 8-46 Uniformity in the Task area 3

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 4	100 x 100	515	437	585	0.85	0.75
	Area circostante 4	128 x 128	488	386	608	0.79	0.64

Figure 8-47 Uniformity in the Task area 4
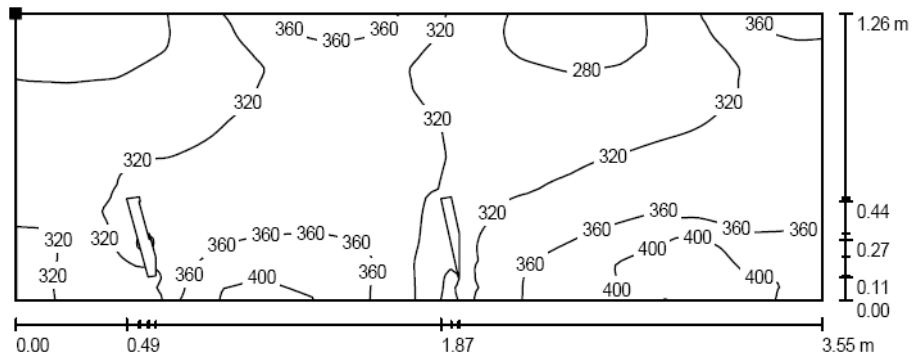
Reticolo: 64 x 128 Punti

E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
328	260	445	0.79	0.58

Figure 8-48 Vertical illuminance on the task area 3
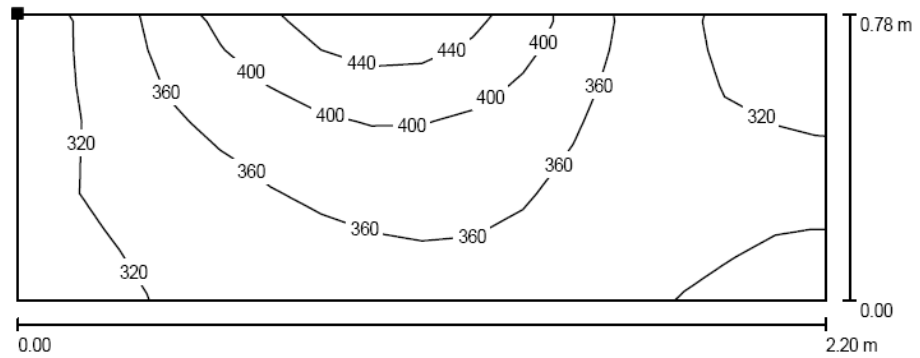
Reticolo: 8 x 16 Punti

E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
353	302	475	0.85	0.64

Figure 8-49 Vertical illuminance on the task area 2

235

Figure 8-50 Iso illuminance curves distribution: 500 lx red, 550 lx brown, 600 lx yellow.

All the task area respects the requirements of the UGR limitation according to the EN 12464-1 the limit value for computer work is under 19. The higher reached value is 18.5 on the task area 3. Our results show that on the task areas we have, with exception of one case, a value near 16 that is only few decimals higher than the requested limit for the task "technical drawing". This kind of task has to be considered as the task with the strictest requirements. However this kind of activity has not to be taken in consideration as a possible task for the user of the office.

No.	Denominazione	Posizione [m]			Dimensioni [m]		Linea di mira [°]
		X	Y	Z	L	P	
1	Superficie di calcolo UGR 1	15.326	11.265	1.200	1.834	1.686	0.0
2	Superficie di calcolo UGR 2	18.545	11.115	1.200	1.674	1.674	0.0
3	Superficie di calcolo UGR 3	16.484	7.641	1.200	3.943	3.361	0.0
4	Superficie di calcolo UGR4	16.413	5.143	1.200	4.038	1.680	0.0

Figure 8-51 UGR value on the investigated surfaces
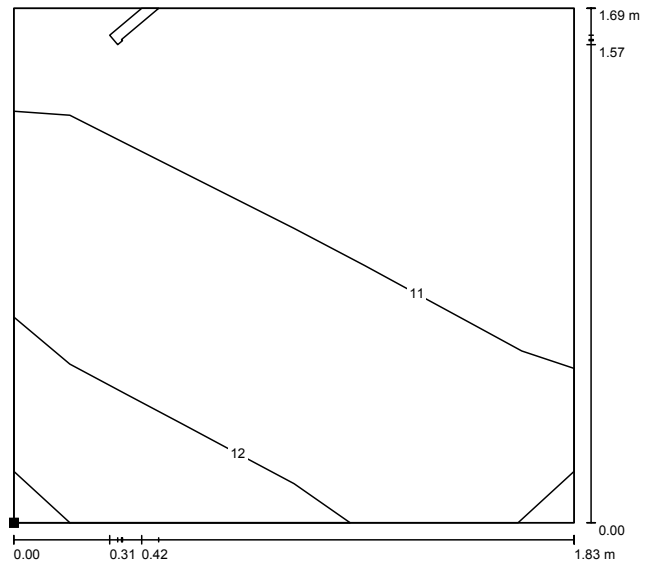
Figure 8-52 UGR value on task area 1
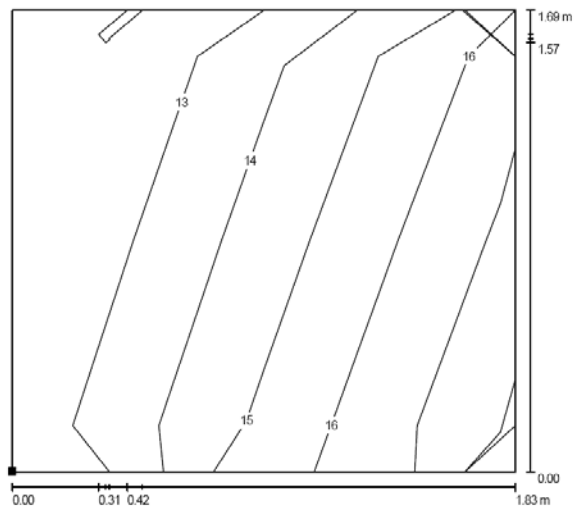
Figure 8-53 UGR value on task area 2
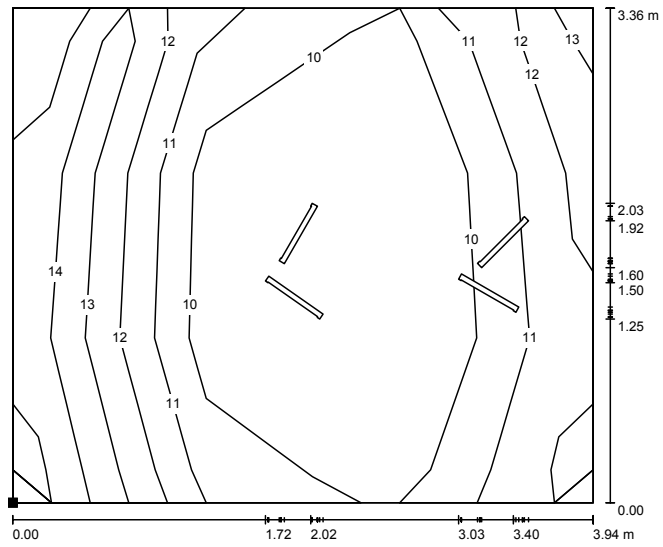
Figure 8-54 UGR value on task area 3
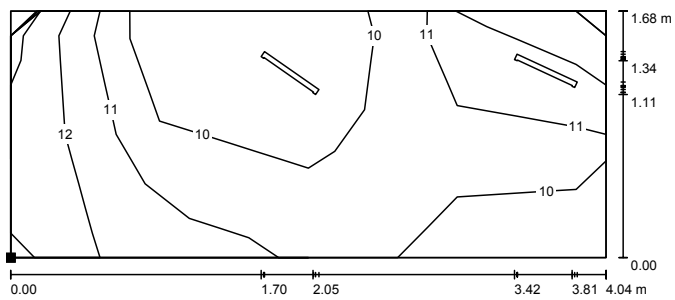
Figure 8-55 UGR value on task area 4
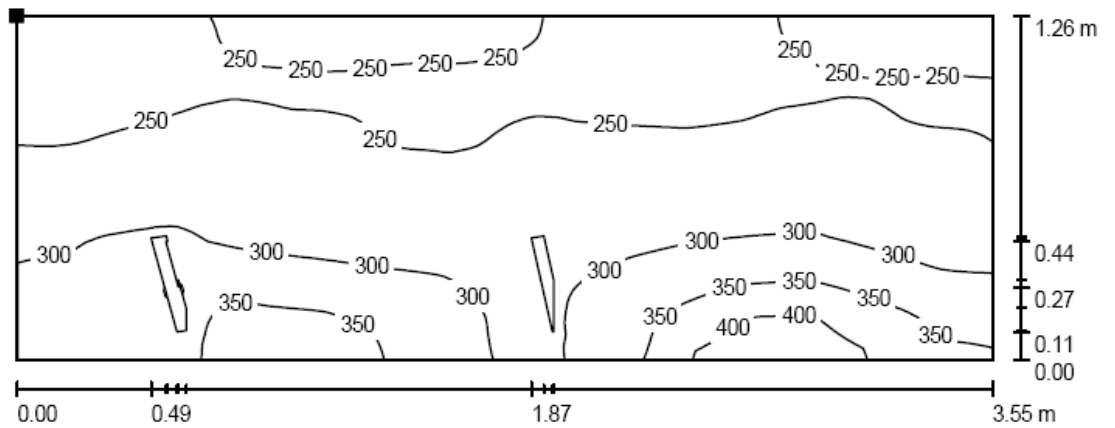
Figure 8-56 Vertical illuminance value on the task area 1

238
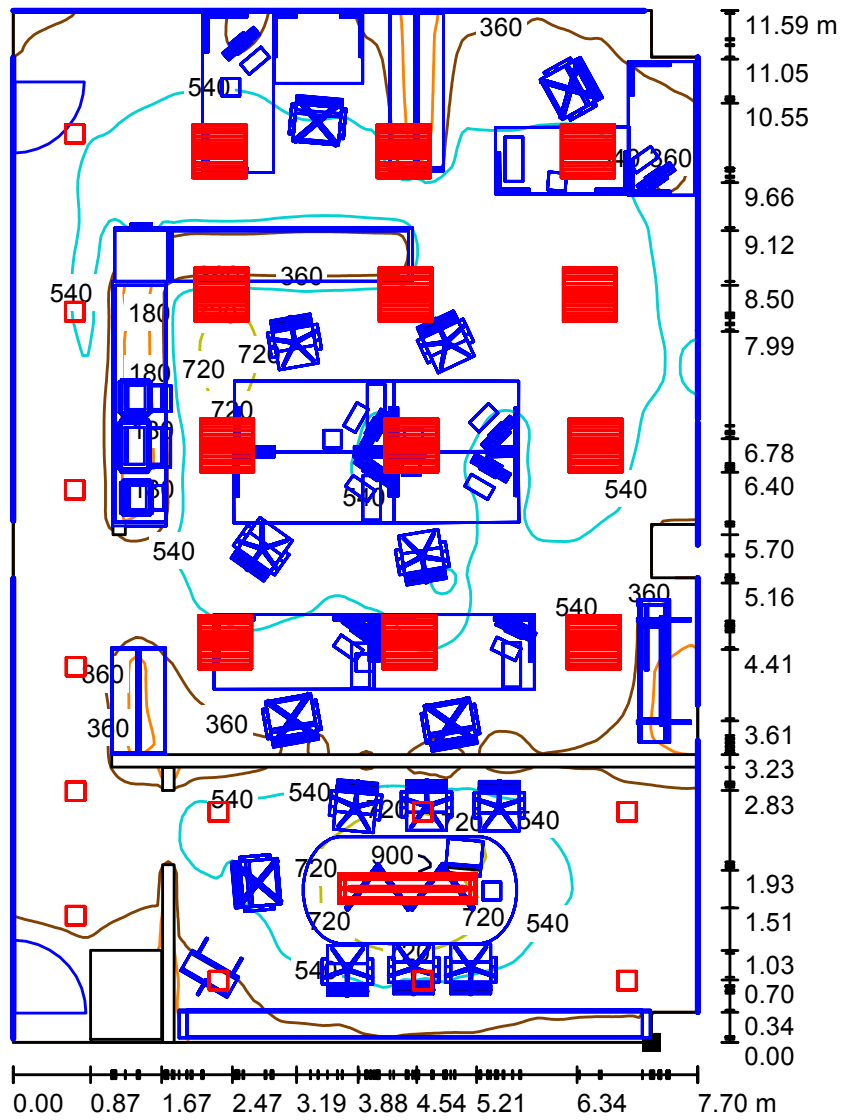
Figure 8-57 Illuminance Isolinee distribution

Figure 8-58 Rendering of the working area

Figure 8-59 Rendering of the meeting room

Total energy consumtion for the lighting system:	1938,89	

Energy consumption for the visual task	1420,13	kWh/year
Parasitic energy consumption for standby	86,46	kWh/year
Parasitic energy consumption for emergency lighting	432,30	kWh/year
Total energy consumption	1938,89	kWh/year
Surface	86,46	m^2
LENI	22,43	kWh/year

Month	Lighting		Visual task		Parasitic + Emerg.	
	kWh	[kWh/m²]	kWh	[kWh/m²]	kWh	[kWh/m²]
Gen	167,58	1,94	124,35	1,44	43,23	0,5
Feb	163,18	1,89	119,95	1,39	43,23	0,5
Mar	159,57	1,85	116,34	1,35	43,23	0,5
Apr	158,77	1,84	115,54	1,34	43,23	0,5
Mag	158,17	1,83	114,94	1,33	43,23	0,5
Giu	158,38	1,83	115,15	1,33	43,23	0,5
Lug	158,17	1,83	114,94	1,33	43,23	0,5
Ago	158,17	1,83	114,94	1,33	43,23	0,5
Set	159,57	1,85	116,34	1,35	43,23	0,5
Ott	161,97	1,87	118,74	1,37	43,23	0,5
Nov	166,38	1,92	123,15	1,42	43,23	0,5
Dic	168,98	1,95	125,75	1,45	43,23	0,5
Total year	1938,89	22,43	1420,13	16,43	518,76	6

Figure 8-60 Energy consumption assessment of the CASE B

Considering the obtained values can be pointed out that the energetic consumption for square meter is relatively low. The calculated value is 16,43 kWh/m^{2}year. This solution satisfies completely the target of the lighting planning according to the EN 12464-1. Moreover it has been accomplished the goal to fulfill the requirements described in the EN 15193 for the solution of lighting quality class "two star". If we sum to the obtained values the parasitic energy consumption and the emergency lighting consumption we obtain that we have a total energy consumption value of 22,43 kWh/m^{2}year. We took in consideration 1 kWh/m^{2}year for the parasitic Energy consumption and 5 kWh/m^{2}anno for the emergency lighting consumption as suggested from the EN standard.

The outcoming calculated value is far lower than the benchmark value suggested from the EN standard (41.4 kWh/m^{2}anno) and shown in Figure 5-20.

CASE C

The Case C is defined by the following characteristics and represents a solution that is rated, in the EN 15193, as three stars lighting quality class. (Class ∗∗∗).

- DALI luminaires with electronic ballast

- Indirect/direct luminaire with optic with micropyramidal structure for the work zone.

- Direct lighting trough recessed down light in ceiling ribbon lumuinaries with mellow light with PMMA optic luminairie for the corridors and perimetral areas. Luminairies with T5 lamps.

- Direct/indirect lighting trough up/downlight pendant luminaire plus recessed downlight in ceiling ribbon lumuinaries with mellow light with PMMA optic luminairie for the meeting room. Luminairies with T5 lamps.

- Presence control

- Constant illuminance system (daylight sensor)

- User oriented scenarios.

- Independent group or single management of the luminaires

8.3.3.1   Peculiar characteristics of CASE C

Also in this solution it has been chosen to foresee square elements (600 mm X 600 mm) plaster ceiling with a free height of 2,7 m. The luminaires are in ceiling and pendant type. The reflection coefficients are the same for all the case studies and are the ones reported in paragraph 8.2. A DALI BUS system has been used for the management of the luminaires switching and the user can switch selecting between different scenarios.

The predicted maintained illuminance is 500 lux and the glare control assessment give as results that UGR level are under <19 with a $L_{65°}$ inferior to 1000cd/m^2.The in pendent luminaires give an high architectonic effect. The T5 lamps driven by electronic ballast help to contain the consumption of energy that is of course higher than in the other two cases. Indirect/direct lighting improves room impression through bright ceiling. A better cylindrical illuminance reached from this optimized solution produce friendly spaces for communication. The use of

direct indirect on the work area gives a really good uniformity. The down lights are used for the corridors and improve the vertical illuminance on the wall and at the entrance. The edge "striscia luminosa" with T5 lamps of 6500K provide a healthy scenario in case of low daylight at the afternoon or in rainy days.
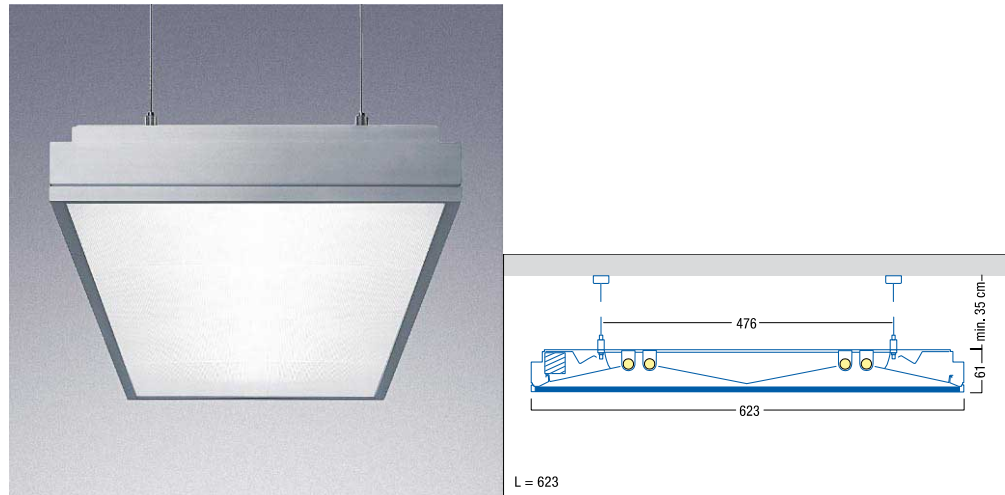

Figure 8-61 Dimmable Recessed luminaire mellow light 2X24W+2X24W T5 with electronic ballast and DALI interface
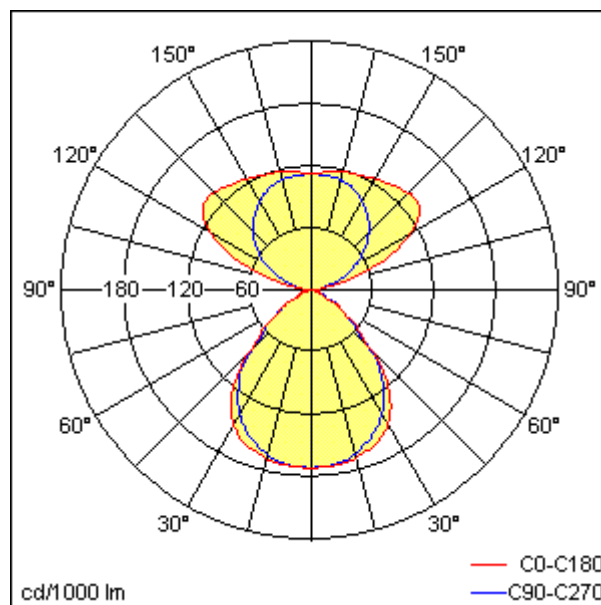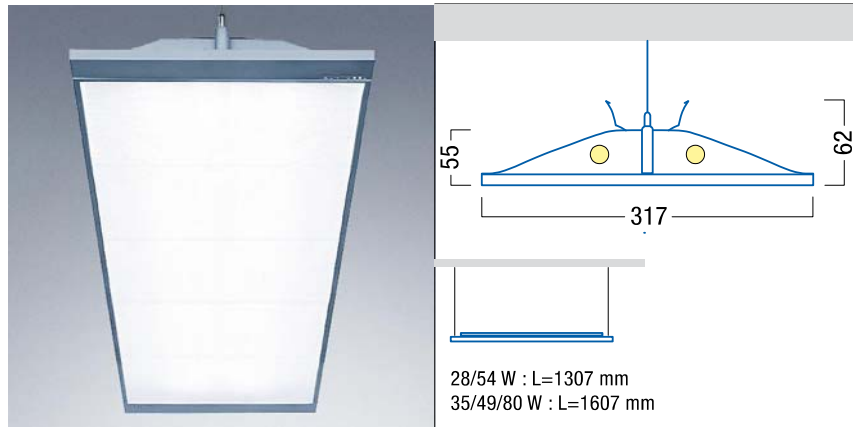

Figure 8-62 Photometric curves of the recessed mellow light luminaires

317

55

62

28/54 W : L=1307 mm
35/49/80 W : L=1607 mm

Figure 8-63 Indirect/direct waveguide luminaire 2 x 80W, for T16, with digitally addressable, dimmerable DALI electronic ballast
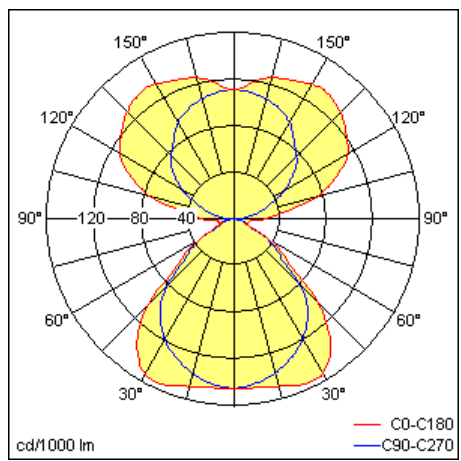
Figure 8-64 Photometric curves of the pendant direct/diffuse luminaire

10
100
68
109
40-91
68
170
34
100
68
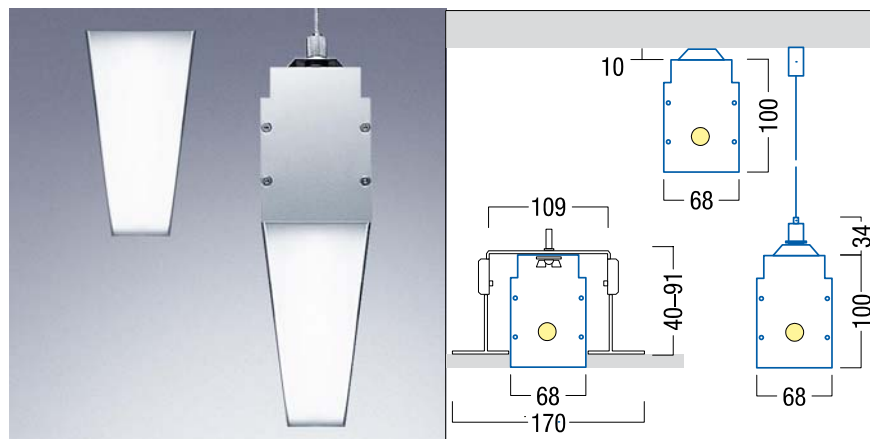
Figure 8-65 In Ceiling downlights with faceted reflector and suspended decorative glass. Compact Fluorescent lamps electronic ballast and DALI interface.
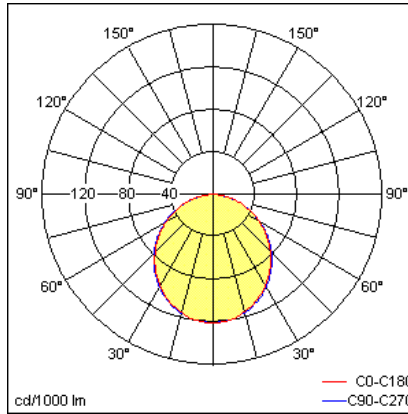
Figure 8-66 Photometric curves of the downlight luminaires

The predicted maintained illuminance is 500 lux and the glare control assessment give as results that UGR level are under <19 with a $L_{65°}$ inferior to $1000cd/m^2$.

The in ceiling luminaires give an appreciable architectonic effect and reduce effectively the energetic consumption due to the usage of the state of the art T5 lamps driven by electronic ballast.
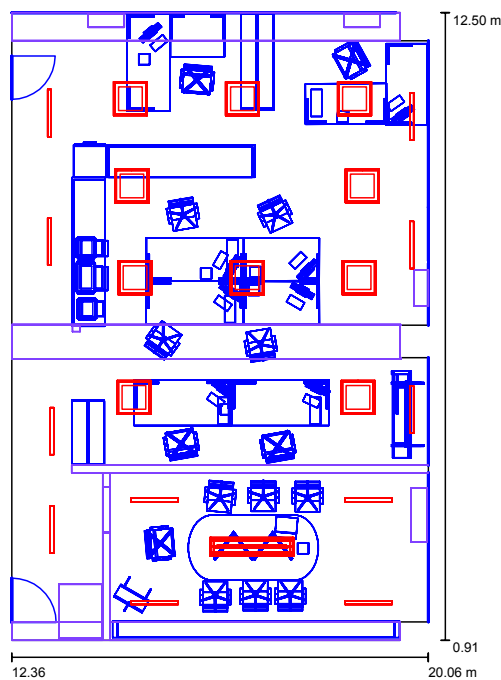
8.3.3.2   *Results CASE C*

Figure 8-67 Luminaires lay-out

This solution present a specific installed power of 19,80 W/m² that means 3.64 W/m²/ for every 100 lx on a floor a net area of 88.49 m².

Figure 8-68 to Figure 8-71 show the more important calculated values that should be taken in consideration for the different task areas. The average maintained illuminance calculated is 809 lux and the lower illuminance on the task 1 is 524 lux. The ratio between the two values gives us the uniformity ratio that could be interpreted as to low according to the standard requirements of the EN 12464-1. To this point we have to say that the lower value reached on the task area 1 depends that the task area confines with the wall whose influence doesn't allow reaching better values. According to that we have to say that the simulation was made with the office completely furnished with pc stations and monitors. The position of the PC monitor inside the task area causes a lower value punctually. Under this consideration this peculiar situation seems to be acceptable. The Average illuminance on the surrounding areas has uniformity higher than the reference values required by the EN 12464-1

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 1	32 x 32	809	524	1065	0.65	0.49
	Area circostante 1	128 x 128	870	655	1101	0.75	0.59

Figure 8-68 Uniformity in the Task area 1

The task area 2 satisfies completely the standard requirements.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 2	8 x 8	885	725	1019	0.82	0.71
	Area circostante 2	128 x 128	778	600	1041	0.77	0.58

Figure 8-69 Uniformity in the Task area 2

For the task area 3 the same consideration of the task area 1 can be done. All in all the situation presents only a punctual deviation from the prescribed uniformity levels that is even weaker than in task area 1.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 3	8 x 16	740	507	879	0.68	0.58
	Area circostante 3	128 x 128	714	569	919	0.80	0.62

Figure 8-70 Uniformity in the Task area 3

The task area 4 satisfies completely the standard requirements.

No.	Denominazione	Reticolo	E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
1	Area di lavoro 4	100 x 100	759	619	868	0.81	0.71
	Area circostante 4	128 x 128	731	607	875	0.83	0.69

Figure 8-71 Uniformity in the Task area 4
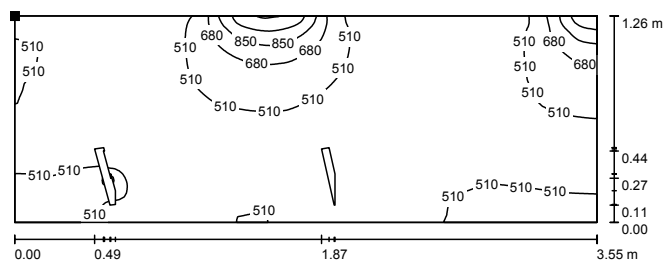
Reticolo: 64 x 128 Punti

E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
503	402	1208	0.80	0.33

Figure 8-72 Vertical illuminance value on the task area 1
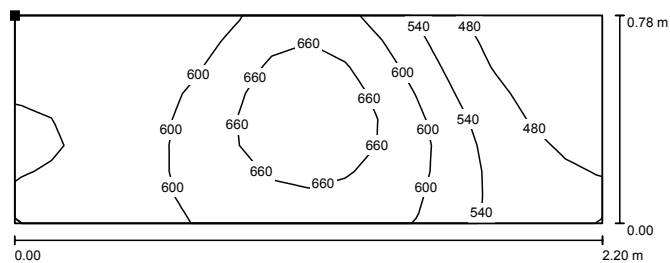
E_m [lx]	E_{min} [lx]	E_{max} [lx]	E_{min} / E_m	E_{min} / E_{max}
577	436	714	0.76	0.61

Figure 8-73 Vertical illuminance on the task area 3
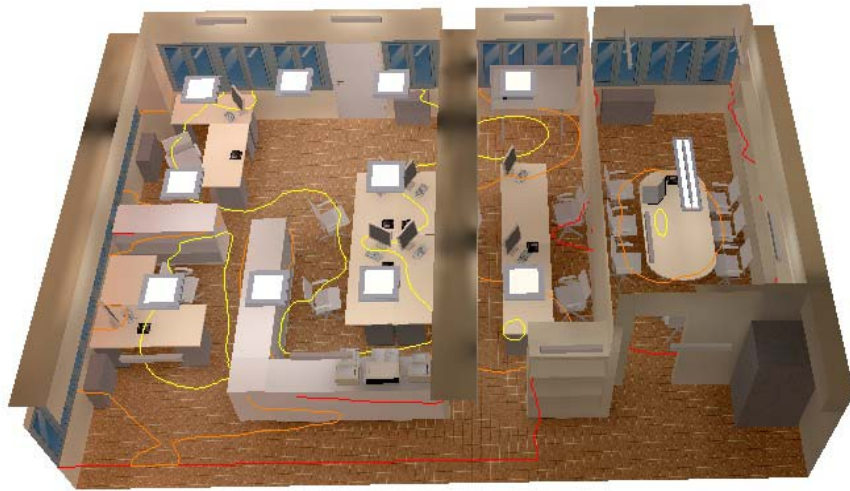
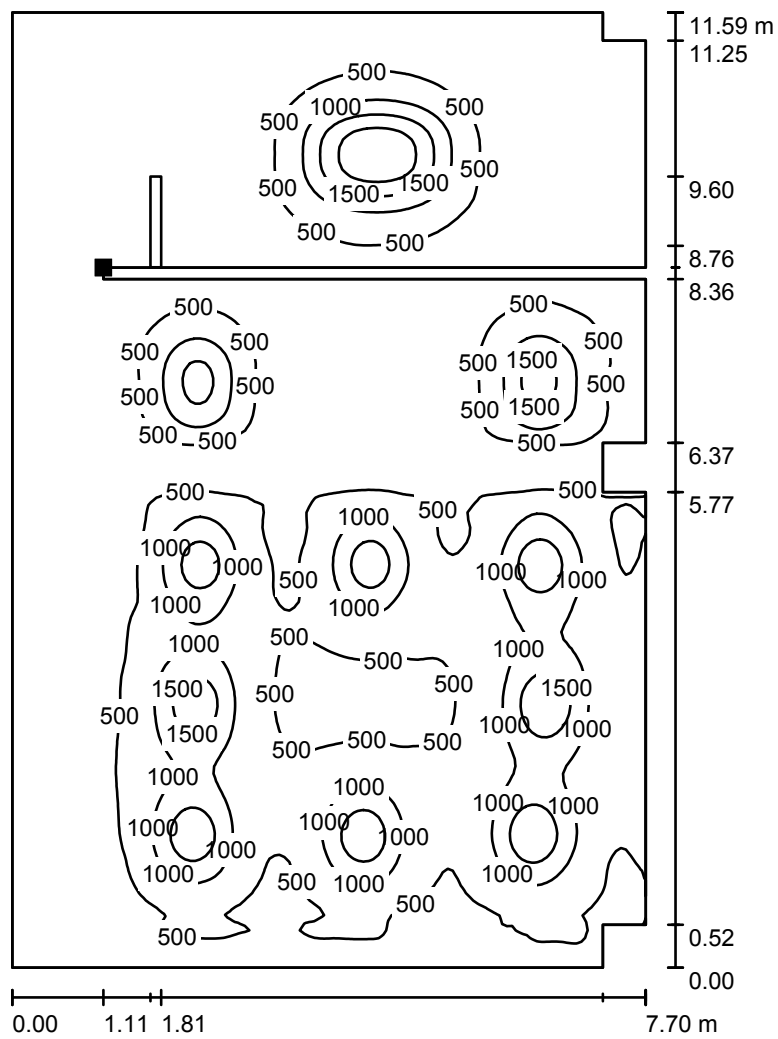*Figure 8-74 Iso illuminance curves distribution: 450 lx red, 550 lx brown, 650 lx yellow.*

Figure 8-75 Luminance distribution on the ceiling cd/m²

No.	Denominazione	Posizione [m]			Dimensioni [m]		Linea di mira [°]
		X	Y	Z	L	P	
1	Superficie di calcolo UGR 1	15.326	11.265	1.200	1.834	1.686	0.0
2	Superficie di calcolo UGR 2	18.545	11.115	1.200	1.674	1.674	0.0
3	Superficie di calcolo UGR 3	16.484	7.641	1.200	3.943	3.361	0.0
4	Superficie di calcolo UGR4	16.413	5.143	1.200	4.038	1.680	0.0

Figure 8-76 UGR value on the investigated surfaces
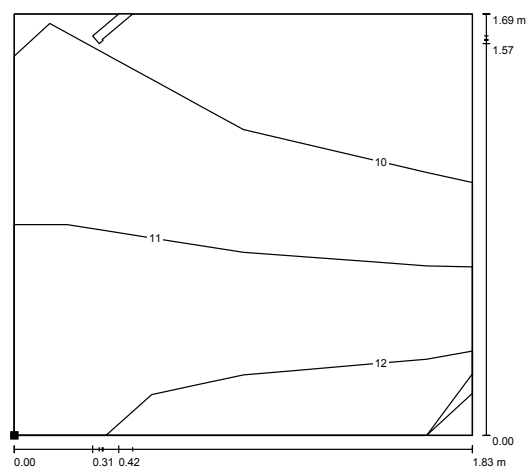
Figure 8-77 UGR value on task area 1
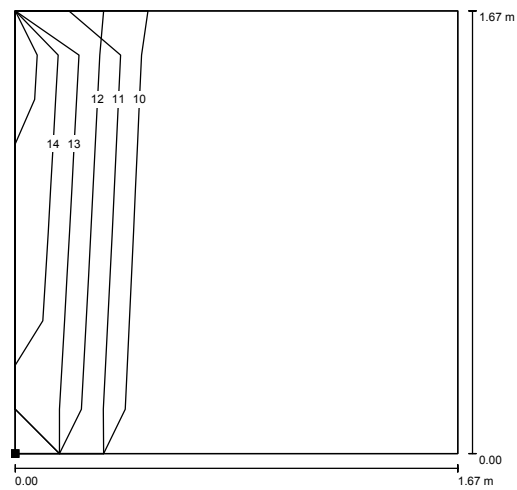
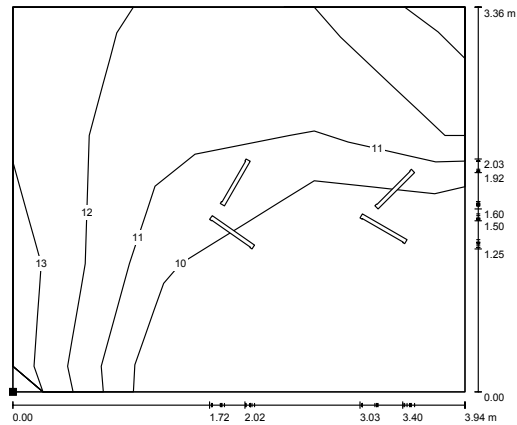*Figure 8-78 UGR value on task area 2*

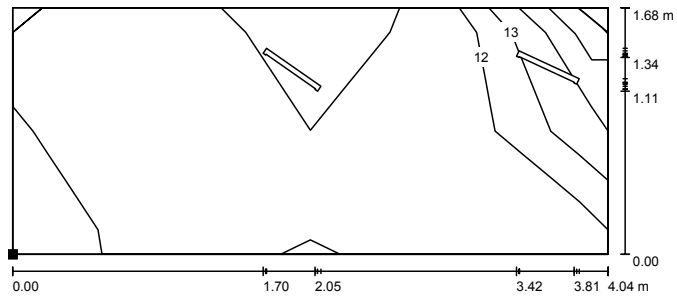*Figure 8-79 UGR value on task area 3*

Figure 8-80 UGR value on task area 4

All the task area respect the requirements of the UGR limitation according to the EN 12464-1, the limit value for computer work is under 19. The higher reached value is 18.5 on the task area 3. Our results shows that on the task areas we have, with exception of one case, a value near 16 that is only few decimals higher than the requested limit for the task "technical drawing". This kind of task has to be considered as the task with the strictest requirements. However this kind of activity has not to be taken in consideration as a possible task for the user of the office.
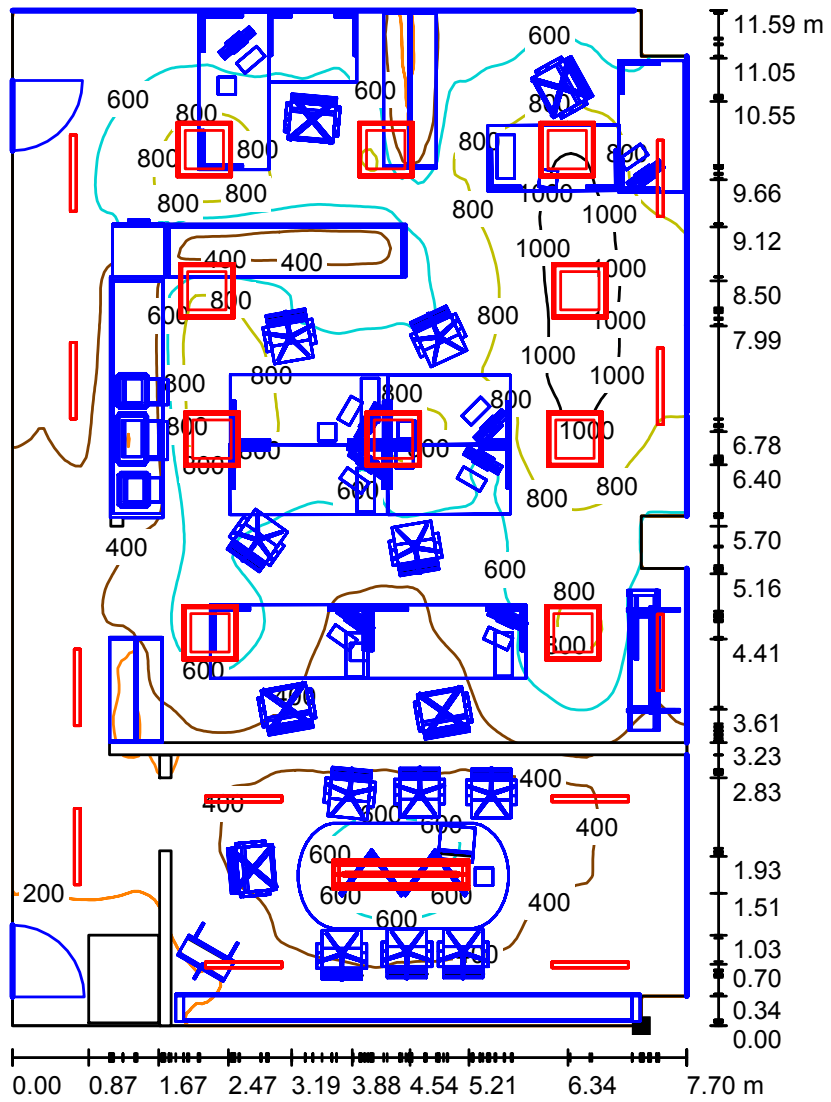
Figure 8-81 Illuminance Isolinee distribution

Figure 8-82 Rendering of the working area

Figure 8-83 Rendering of the meeting room

Total energy consumtion for the lighting system:	2261,56

Energy consumption for the visual task	1742,80	kWh/year
Parasitic energy consumption for standby	86,46	kWh/year
Parasitic energy consumption for emergency lighting	432,30	kWh/year
Total energy consumption	2261,56	kWh/year
Surface	86,46	m²
LENI	26,16	kWh/year

Month	Lighting		Visual task		Parasitic + Emerg.	
	kWh	[kWh/m²]	kWh	[kWh/m²]	kWh	[kWh/m²]
Gen	201,96	2,34	158,73	1,84	43,23	0,5
Feb	192,06	2,22	148,83	1,72	43,23	0,5
Mar	183,96	2,13	140,73	1,63	43,23	0,5
Apr	182,16	2,11	138,93	1,61	43,23	0,5
Mag	180,81	2,09	137,58	1,59	43,23	0,5
Giu	181,27	2,1	138,04	1,6	43,23	0,5
Lug	180,81	2,09	137,58	1,59	43,23	0,5
Ago	180,81	2,09	137,58	1,59	43,23	0,5
Set	183,96	2,13	140,73	1,63	43,23	0,5
Ott	189,37	2,19	146,14	1,69	43,23	0,5
Nov	199,27	2,3	156,04	1,8	43,23	0,5
Dic	205,12	2,37	161,89	1,87	43,23	0,5
Total year	2261,56	26,16	1742,8	20,16	518,76	6

Figure 8-84 Energy consumption assessment of the CASE C

8.4.   Real case realization.

Figure 8-85 Site of the offices

The offices are sited in an industrial building in North-east Italy in Udine between Venice and Trieste. The orientation is shown in Figure 8-86.
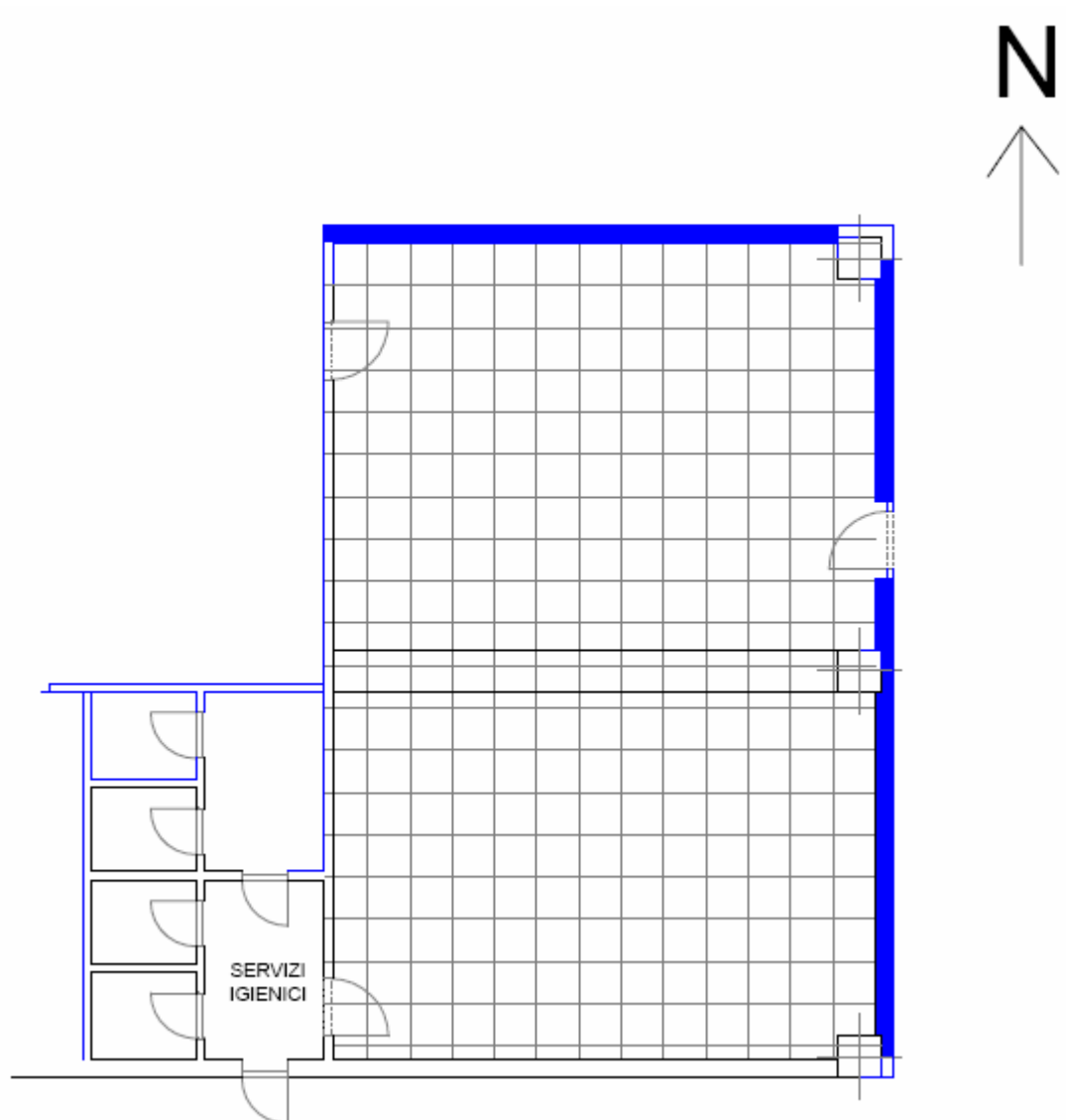
Figure 8-86 Orientation of the offices and fenestration.

The case study that has been chosen for the realization is the case B. This case was the one that has realized the expectation of the owner economically and from the lighting quality point of view. The first step was to refurbish all the electrical facilities. During this phase all the ducts for the bus and power connection has been posed inside the false ceiling. Every luminaires sensor and power line has been predisposed.

After that the electrical board has been build the lighting management board has been connected. All the actuators in the lighting management board are protected from under a fuse.

The first actuator (type 1) is an input device with four separately addressable inputs for the integration of conventional momentary action light switches into a bus-connected light and room management system. Depending on the addressing of an input, all actuators of a room or one actuator group of the room can be operated. To this actuator are connected the ballast actuator (type XX)

The second actuator (type 2) is an input device with two separately addressable inputs for the integration presence detectors. Every input has two terminals "On" and "Off".

The third actuator (type 3) is a bus power supply with 15VDC for up to 100 bus subscribers, cascadable, resistant to sustained short circuit. On the output side are positioned the connection for bus line, with reversible polarity, for control of peripheral devices.

The fourth actuator (type 4) is a relay output device with a relay contact for switching of lamps for network voltages of up to 230/240V.
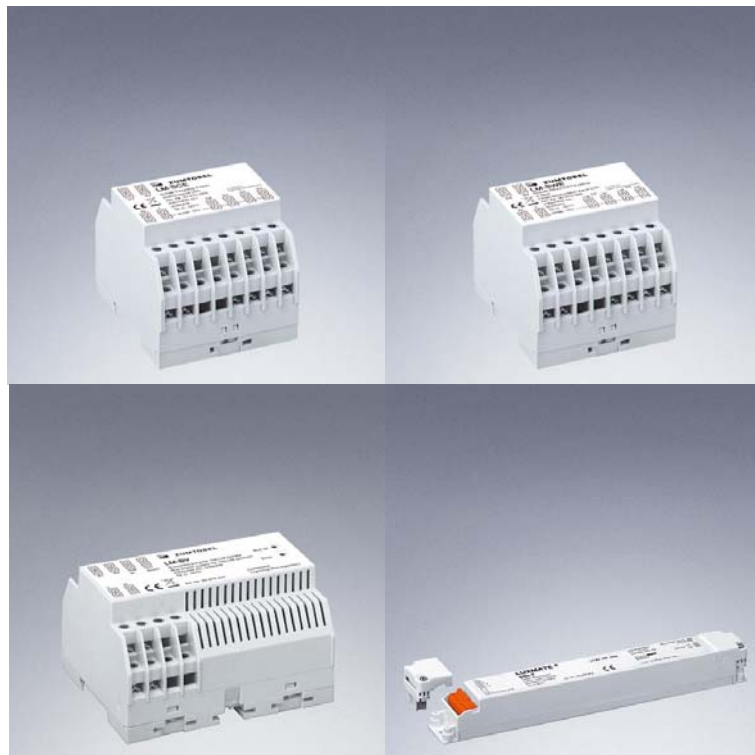

Figure 8-87 Actuators in the lighting management board

Figure 8-88 Lighting management board

The presence sensor is connected to the actuator type 4 and gives an On/off signal. In case of user absence after 10 minutes the light switches automatically off.

Figure 8-89 Power and Bus Connections

An actuator (type 5) drives the ceiling-mounted sensor for measuring the daylight entering the room through the window and give the collected information to the related actuator in the lighting management board. The external light sensor is connected to dim the lights according to the external light in a regulation range from 0% to 100% (see Figure 8-91)
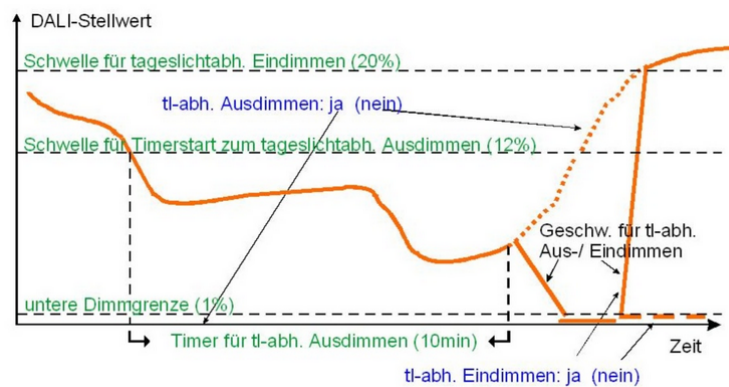
. Figure 8-90 External light sensor

Figure 8-91 External daylighting regulation curves

Each group of luminaires is separately controlled by an actuator (type 6) also connected to the lighting management board. This actuator drives the luminaires according to the selected scenario. All the system is controlled by 6 switching points. Two master points for the scenario control and 4 for the manual control of the different groups of luminaires. The four groups of luminaires supply the 4 different task areas.

Figure 8-92 Master control points

The first master switching point is an input device for the commissioning, configuration and operation of a complex bus-controlled light and room management system. Five frequently used light and glare protection situations for the different activities in the individual rooms can be configured as room scenarios (so-called scenes), saved, and recalled at the press of a button when needed. In connection with a central automation computer or a local daylight controller, luminaires and (in the case of a central automation computer) glare protection are controlled dependent on available daylight with the input device being used for defining the system points, control characteristic curves and offset points. An integrated display provides a dialogue to support all configuration and commissioning steps and enables simple control of the selected settings.

The second master switching point is a control point with circularly arranged keys for recalling three room situations (so-called scenes). The active scene is indicated by a green LED.

The whole installation was divided in two phases. The first one regards the preparation of the power and BUS lines. Before this phase the old plaster ceiling modules had been removed and only the supports of the old ceiling had been left in place.

Figure 8-93 Old ceiling

After this phase the supports of the old ceiling had been replaced with a new structure and the new plaster ceiling module of 600 mm x 600 mm had been embedded. After the construction of the new ceiling the luminaires had been installed and connected and the Lighting control board had been assembled.

Figure 8-94 Old luminaires and old plaster ceiling

The whole system has been programmed to disable the functioning of the luminaires in the case that the task areas should be supplied with 300 lux from the day-light. The chosen luminaires are described in CASE B.

Figure 8-95 New luminaires and new plaster ceiling

Figure 8-96 Programming phase of the system

After the installation of the system another device has been installed into the management board (actuator type 7). This device enables the remote control of the devices form a PC. Moreover it is used to estimate the consumption of energy according to the metering requirements of paragraph 8.2.2.
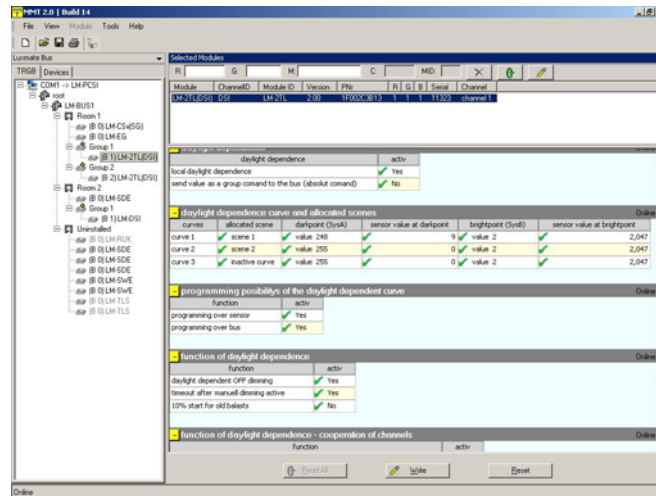
Figure 8-97 PC assistant configuration software with metering tool

8.5.   Measurements

The illuminance of the new offices has been measured after 200 h of functioning of the entire system without dimming. After this first period the whole system has been programmed as described in the previous paragraph. The measures were made according to UNI 10380 Appendix C. The EN 12464-1 foresees that the measurement should be taken in the grid points used for the calculation. This kind of procedure can not be used easily in spaces with furniture. In those specific case the simulation use a very thick grid that is quite difficult or even impossible to use as measurement grid. Although UNI 10380 has been replaced by the EN 12464-1 for all the prescriptions regarding the lighting requirements it represents the only Italian standard reference that gives indication how the measurement grids or points can be realistically calculated in case of illuminance measures for indoor workplaces with furniture. According to this standard the system was measured at night time after that the luminaires had been working for more than one hour. In refurbished spaces the measures were done according the following principles:

- The spaces have been subdivided in work zones.

- Each work zone refers to a specific task.

- Maintenance coefficient of 0,8

- The lowest number of measurement point for each zone should be not inferior to 9 points.

$$K = \frac{a \times b}{h \times (a + b)}$$

8-1

- The average illuminance was calculated through the following equation.

$$E_m = \frac{1}{n} \sum_{x=1}^{n} E_x$$

8-2

X is a measurement point.

N is the number of measurement point taken in consideration.

E_x is the measured illuminance in the x measurement point expressed in lux.

The digital light meter used is a HT170N with a range of measurement between 0.1 lux and 50.000 lux. Its precision tolerance is of 5% on the measured values

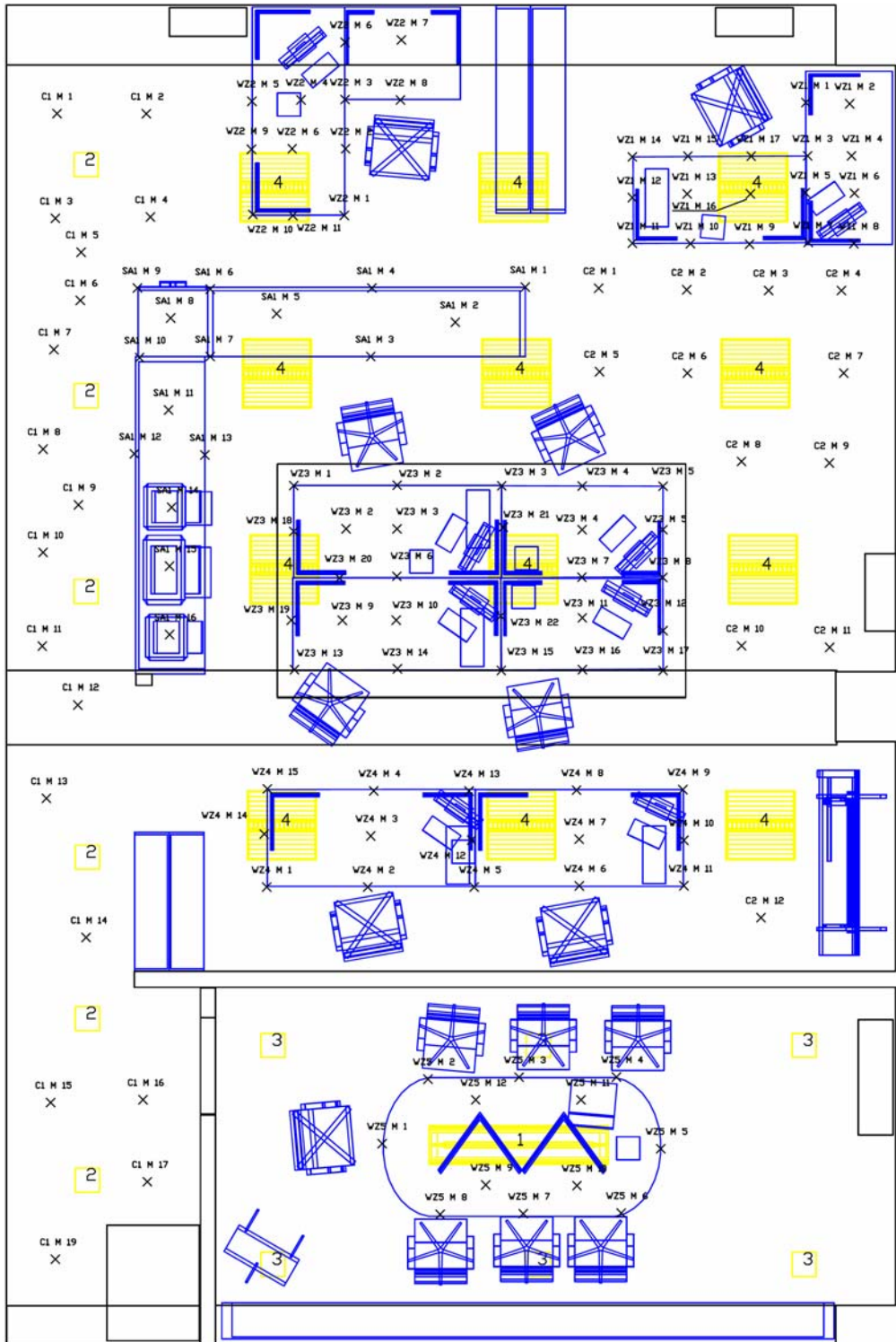*Figure 8-98 Digital light meter.*
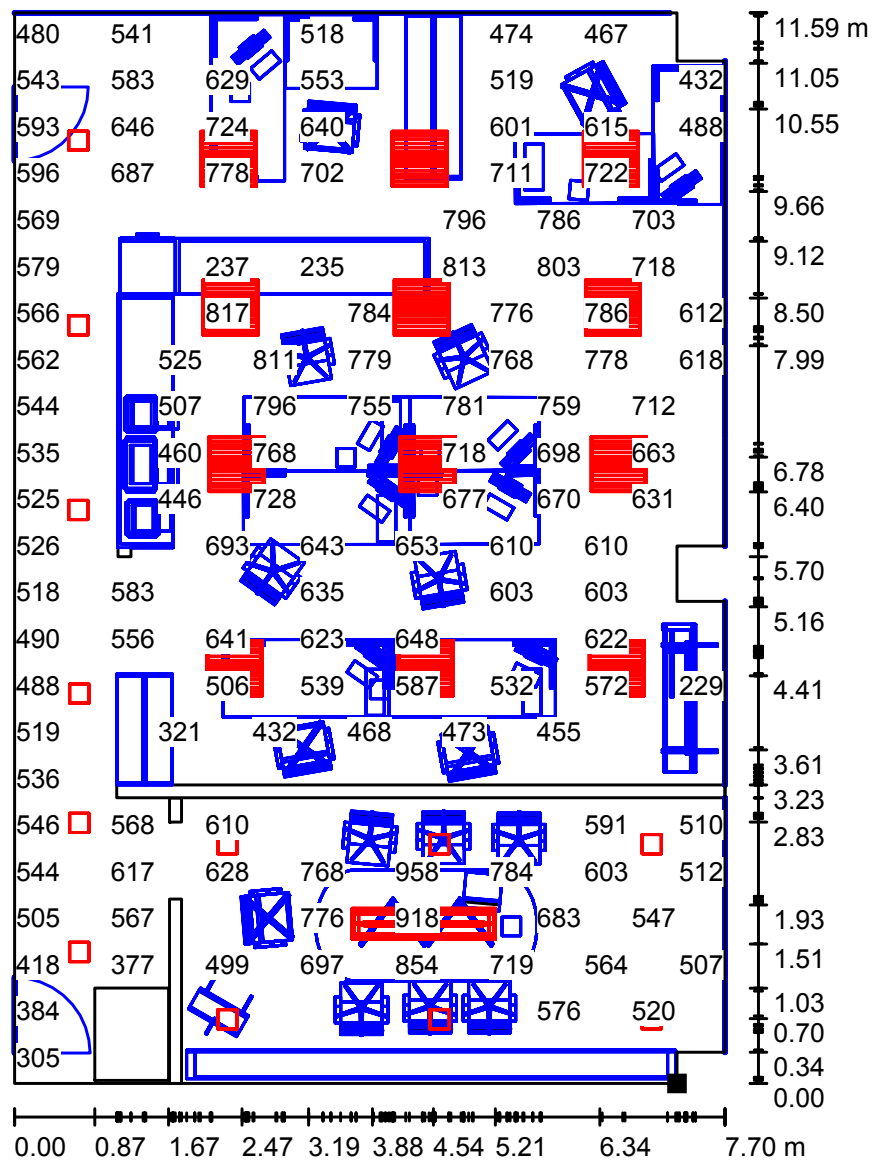
Figure 8-99 Measurement points

Figure 8-100 Simulation values on a wide grid without taking in account the specific task areas.

The values in Figure 8-100 are simulation results calculated at 0,85 m from the floor. Some of them are strongly influenced from the furnitures. The values under 300 lux depend on the fact that in the L shaped furniture has a height of 1,2 m. The measured values refer to the real task area and are taken at the real height of the task area:

- 0.2 m height for corridors

- 0.85 m on work tables task areas (5 cm above the tables height)

- 1,2 m on the L shaped furniture

ZONE		N°	VALUE
WZ	1 M	1	550
WZ	1 M	2	540
WZ	1 M	3	520
WZ	1 M	4	560
WZ	1 M	5	570
WZ	1 M	6	545
WZ	1 M	7	660
WZ	1 M	8	500
WZ	1 M	9	545
WZ	1 M	10	750
WZ	1 M	11	780
WZ	1 M	12	790
WZ	1 M	13	760
WZ	2 M	14	725
WZ	3 M	15	740
WZ	4 M	16	800
WZ	5 M	17	720
Uniformity			0,625
Em			520,24

ZONE		N°	VALUE
WZ	2 M	1	647
WZ	2 M	2	691
WZ	2 M	3	710
WZ	2 M	4	700
WZ	2 M	5	725
WZ	2 M	6	810
WZ	2 M	7	900
WZ	2 M	8	905
WZ	2 M	9	800
WZ	2 M	10	790
WZ	2 M	11	785
Uniformity			0,7149
Em			615,49

ZONE		N°	VALUE
WZ	3 M	1	890
WZ	3 M	2	870
WZ	3 M	3	890
WZ	3 M	4	875
WZ	3 M	5	905
WZ	3 M	6	887
WZ	3 M	7	912
WZ	3 M	8	770
WZ	3 M	9	875
WZ	3 M	10	892
WZ	3 M	11	920
WZ	3 M	12	846
WZ	3 M	13	820
WZ	3 M	14	850
WZ	3 M	15	850
WZ	3 M	16	930
WZ	3 M	17	840
WZ	3 M	18	790
WZ	3 M	19	990
WZ	3 M	20	920
WZ	3 M	21	820
WZ	3 M	22	850
Uniformity			0,7778
Em			697,89

ZONE		N°	VALUE
WZ	4 M	1	801
WZ	4 M	2	632
WZ	4 M	3	690
WZ	4 M	4	735
WZ	4 M	5	740
WZ	4 M	6	765
WZ	4 M	7	793
WZ	4 M	8	823
WZ	4 M	9	620
WZ	4 M	10	790
WZ	4 M	11	815
WZ	4 M	12	690
WZ	4 M	13	790
WZ	4 M	14	632
Uniformity			0,7533
Em			589,49

ZONE		N°	VALUE
WZ	5 M	1	791
WZ	5 M	2	768
WZ	5 M	3	754
WZ	5 M	4	764
WZ	5 M	5	755
WZ	5 M	6	765
WZ	5 M	7	793
WZ	5 M	8	823
WZ	5 M	9	927
WZ	5 M	10	1020
WZ	5 M	11	1050
WZ	5 M	12	1070
Uniformity			0,7047
Em			685,33

ZONE		N°	VALUE
SA	1 M	1	654
SA	1 M	2	547
SA	1 M	3	510
SA	1 M	4	385
SA	1 M	5	351
SA	1 M	6	562
SA	1 M	7	584
SA	1 M	8	545
SA	1 M	9	620
SA	1 M	10	546
SA	1 M	11	526
SA	1 M	12	495
SA	1 M	13	490
SA	1 M	14	520
SA	1 M	15	529
SA	1 M	16	540
Uniformity			0,5367
Em			420,2

ZONE		N°	VALUE
C	1 M	1	405
C	1 M	2	403
C	1 M	3	402
C	1 M	4	456
C	1 M	5	595
C	1 M	6	446
C	1 M	7	546
C	1 M	8	532
C	1 M	9	481
C	1 M	10	443
C	1 M	11	420
C	1 M	12	380
C	1 M	13	421
C	1 M	14	446
C	1 M	15	427
C	1 M	16	395
C	1 M	17	394
C	1 M	18	391
C	1 M	19	370
Uniformity			0,6218
Em			351,71

ZONE		N°	VALUE
C	1 M	1	420
C	1 M	2	394
C	1 M	3	404
C	1 M	4	420
C	1 M	5	382
C	1 M	6	362
C	1 M	7	341
C	1 M	8	368
C	1 M	9	384
C	1 M	10	367
C	1 M	11	380
Uniformity			0,8119
Em			307,05

Figure 8-101 Measured values (lux)

In Figure 8-101 are listed the measured values. Em is the Average maintained illuminance. The measured values are expressed in lux. For the calculation of the Average maintained illuminance a maintenance factor of 0,8 has been taken in consideration.

The different measure zones are:

- WZ 1 Work zone 1 = task area 2

- WZ 2 Work zone 2 = task area 2

- WZ 3 Work zone 3 = task area 3

- WZ 4 Work zone 4 = task area 4

- WZ 5 Work zone 5 = task area 5 (Meeting room)

- SA 1 Surrounding area 1 = L shaped furniture.

- C1/C2 Corridors

The Measures show a quite good correspondence with the simulation results and practically a total respect of the standard requirements.

Figure 8-102 The lighting system without daylight control (left) and with day light control (right)

Figure 8-103 Different pictures of the realized system

8.6. Conclusions

This study has investigated the relationship between lighting quality and Energy consumption in offices. This thematic is really complex and require a lot of attention if comparisons between different case studies are made. The lighting solution is always different from case to case and only few differences between the characteristics of the investigated cases can affect the comparability of the study. The parameters that rules the lighting quality assessment are different and most of the times they are subjective. In our attempt to confront different choices we had to pay attention to stay realistic in the assessment of three cases so that the best choice could be chosen and realized. The highest risk has been the one to investigate too many theoretical aspects that on hypothetical level cannot be taken in consideration. In real cases a lot of the variables linked to aspects like

architectural rating of the spaces or geometrical forms and index of the spaces or availability of square meters per user are constrained to the costumers need. To take into consideration all the variables that participate to the quality lighting assessment all in one assessment model in impossible. The best choice is to restrain the assessment to those parameters that can be measured and estimated. The scope of this study is not to describe the theoretical aspects the lighting quality but to investigate a real case and to determine the energetically involvement of different lighting strategy representing different lighting quality. We started with a review of the lighting theory and fundamentals to facilitate the readers to understand the process of our investigation. We paid a lot of attention to all the aspects concerned with the office environment like office ergonomics and offices lighting issues. We made a review of the lighting standards in force in particular of the new European standard EN 15193. We have pointed out the most important parameters that affect energy consumption and finally we have investigated three possible solutions for a real case study and the following construction of the chosen solution. The results of our investigation pointed out that the benchmark values for the energy consumption indicated in the European standard are for the Italian situation by far too high and quite distant from the real technological values that can be obtained. Moreover has been pointed out that there is a quite linear relationship between quality level and energy consumption and that there is a raise of the 16,13 % between the class " * " and the class " ** "and a raise of 16,62 % between the class " ** " and the class "***". All those values should be taken consideration and weighed according to the specific investigated case. We have to underline that this raise is not really strong and that the more energy expenses are worth when compared to the benefits on the user deriving from a better work environment.

Strongly to underline is the importance of the management system that helps to lower the energy consumption drastically. The utilization of the presence control and of the daylight control has helped to lower in average 35% of the energy consumption. These results are obtained with one of the worst orientation considering that the fenestrations of the offices are Nord and East oriented.

CASE STUDY	Lighting Quality Class (EN 15193)	Presence Control	Daylighting Control	Estimated energy consumption	Banchmark values for energy
A	*	NO	NO	27,23	42,1
A-BIS	*	YES	YES	18,81	32,2
B	**	YES	YES	22,43	41,4
C	***	YES	YES	26,16	50,6

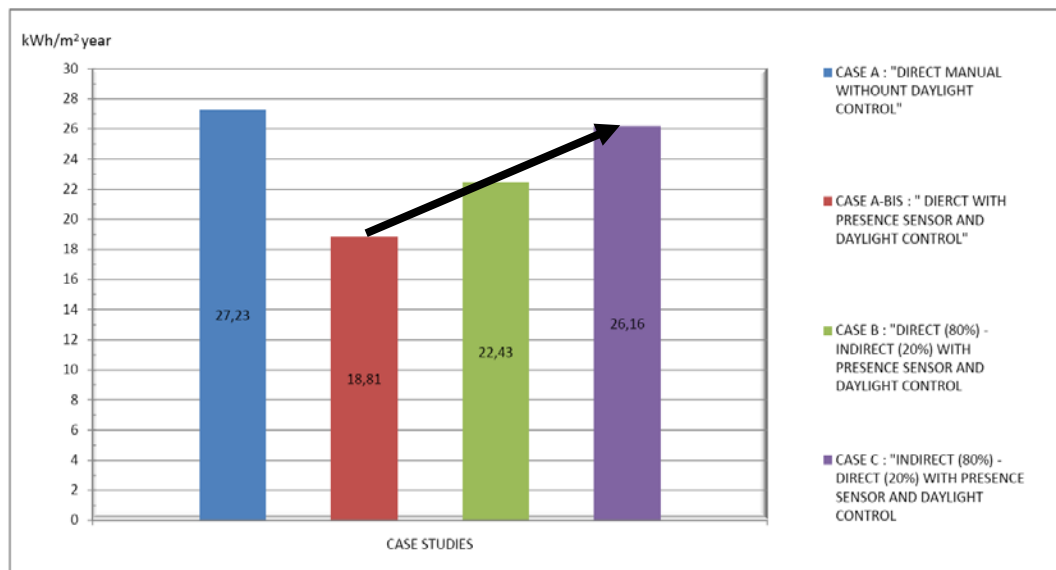Figure 8-104 Comparison between energy consumption EN 15193 Benchmark values and the calculated values.

Figure 8-105 Comparison between energy consumption EN 15193 Benchmark values and the calculated values.

Lighting occurs in an architectural context, whether interior or exterior. High-quality lighting is responsive to the architectural form, composition, and style. The integration with the architecture conveys meaning and contributes to the observer's understanding of the space. Light that ignores architecture can violate human needs. Specifying luminaires that are too tall to fit in the plenum space could delay the completion of a construction project. Costs frequently influence and constrain lighting system choices. Purchasers always tend to be very sensitive to first costs, but installation, operation, and maintenance costs can outweigh first costs in a complete economic analysis. Any lighting solution fails if maintenance or operating costs are higher than common practice. But reduced energy use should not be regarded merely as a compliance with regulation; this is a responsibility toward the ongoing environmental health of our planet and the well-being of future generations.

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