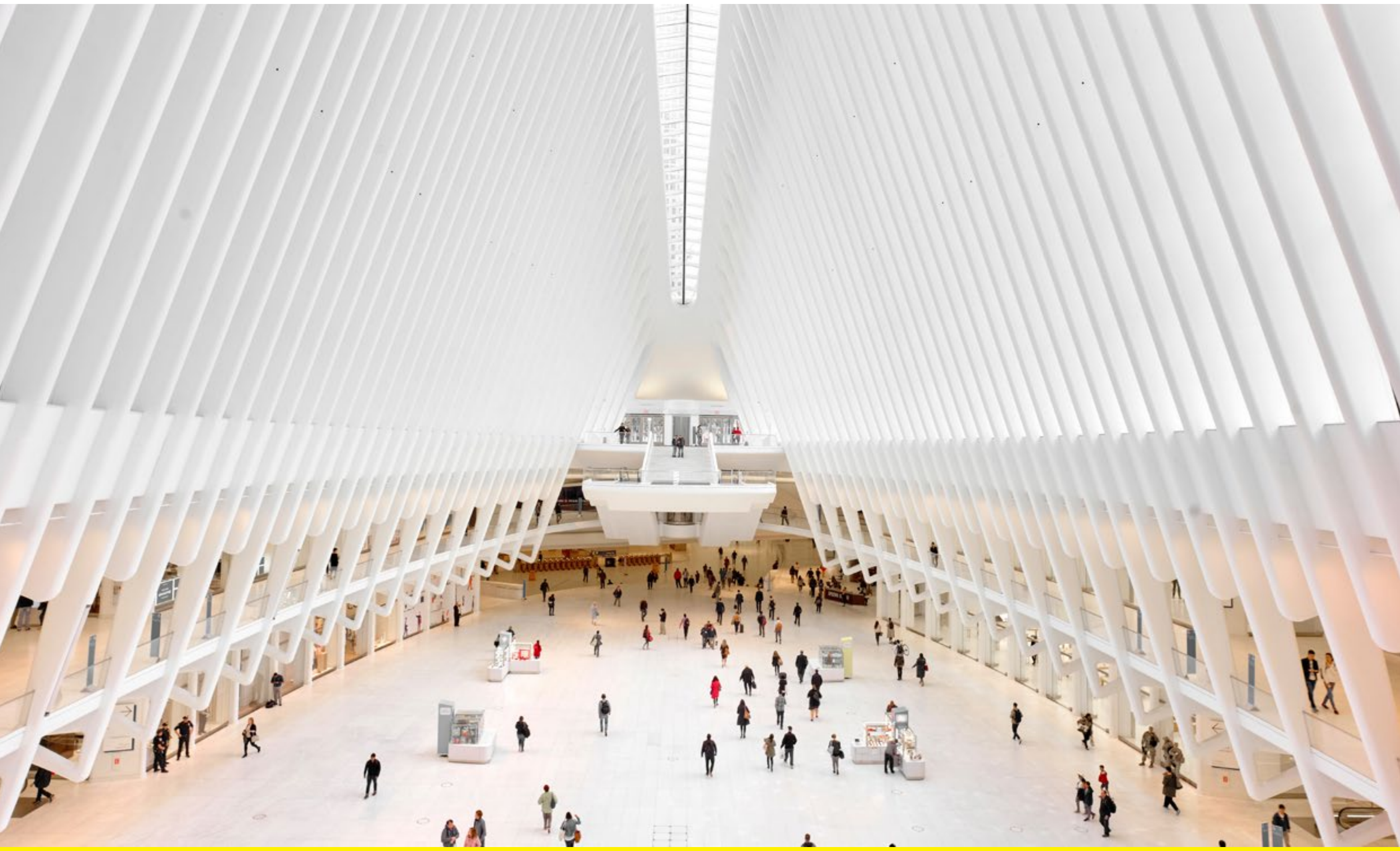
PREMIUM LIGHT PRO

This project is funded by the European Union

Indoor Lighting

in the Public and Private Service Sectors

Guidelines



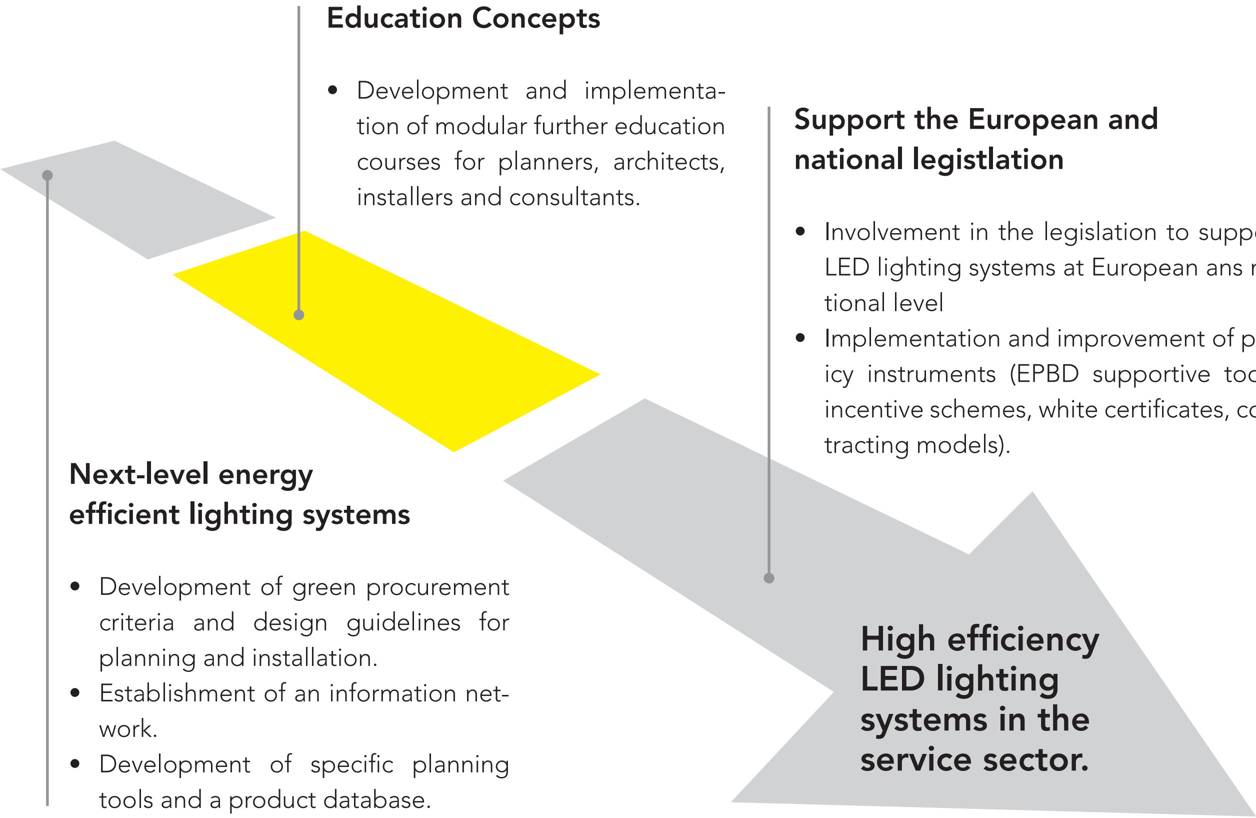
About Premium Light Pro

Premium Light Pro is an EU H2020 project (2016-19) concerning implementation of energy efficient LED lighting systems (indoor and outdoor lighting) in the private and public sectors by development of policy instruments designed in cooperation with stakeholders from the supply and demand side market including:

- Development of procurement criteria
- Development of guidelines for indoor and outdoor lighting
- Collection of Best Practice cases
- Establishment of an information platform
- Development of specific planning tools and a product database
- Execution of modular education courses for architects, installers, consultants etc.

Premium Light Pro will also support the ongoing development of EU regulation (ecodesign, labelling and EPBD) as well as national legislation policy instruments e. g. EPBD supportive tools, incentive schemes, white certificates and contracting models. See more at www.premiumlightpro.eu.

Services provided by Premium Light Pro



Overall, there is a strong potential for substantial energy savings by implementation of adequate policies facilitating the market penetration of highly efficient LED lighting systems.

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How to Use the Guidelines

The guidelines are structured as shown below.

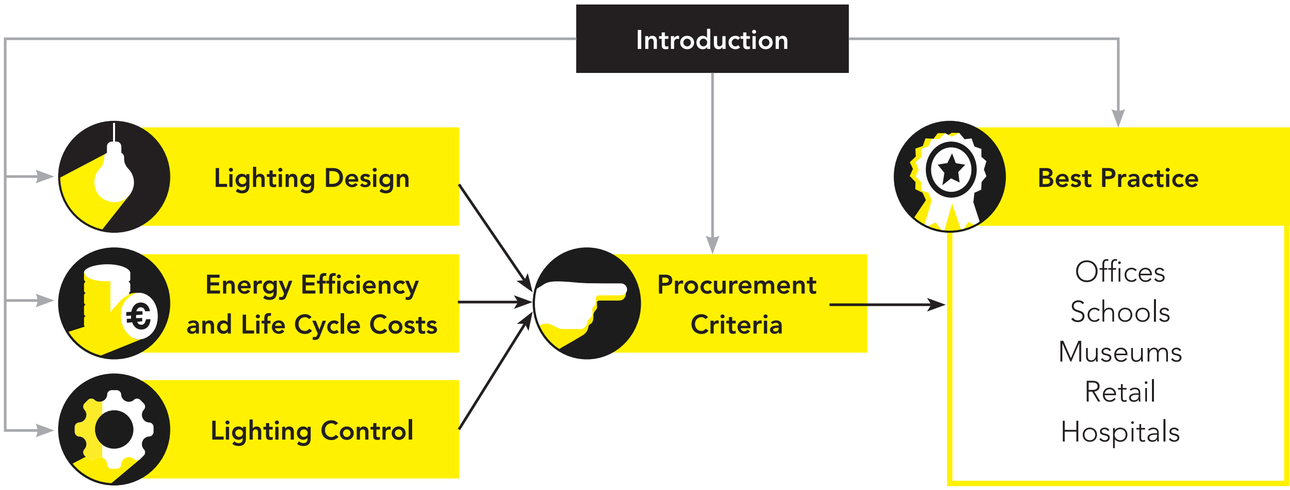


Figure 1 *Procurement criteria is the core of the guidelines*

After being introduced to the general benefits of using LED lighting, the various stakeholders can apply the guidelines in different ways:

1 **Procurement staff and decisions makers** can go directly to the Procurement Criteria, (p. 26). Additionally they might search for background information in:
  - **a** Lighting Design chapter (lighting quality) (p. 7).
  - **b** Energy efficiency and LCC (savings, costs and comparison of solutions) (p. 15).
  - **c** Lighting Control (controls, smart lighting and human centric lighting) (p.19).
  - **d** Best Practice (for the type of building and room in the procurement) (p.33).

2 **Installers** may search in the Best Practice chapter (p.33) for tips as well as for quality criteria in the Procurement chapter.

3 **Energy advisors and ESCO lighting engineers** should consult the Energy Efficiency and LCC chapter (p.15) and the Best Practice chapter (p.33).

4 **Planners, architects, indoor designers and consultants** might search in various parts of the guidelines depending on the content of their actual activity.

List of Content

Acronyms and Abbreviations

AFV	Abrupt Failure Value
ANSI	American National Standards Institute
CCT	Correlated Colour Temperature
CIE	Commission Internationale de l'Éclairage (Illumination)
Cd	Candela, SI unit of luminous intensity.
CFL	Compact Fluorescent Lamps
CRI	Colour Rendering Index
DALI	Digital Addressable Lighting Interface (control protocol)
DSE	Display Screen Equipment
Duv	Chromatic distance to Planckian locus
EC	European Commission
ECEEE	European Council for an Energy Efficient Economy
EPA	Environmental Protection Agency (in Denmark)
EPBD	Energy Performance of Buildings Directive
ESCO	Energy Service Company
GLS	General Lighting Service (nondirectional incandescent lamp)
HCL	Human Centric Lighting
IEA SSL	International Energy Agency 4E Solid State Lighting Annex
IEC	International Electrotechnical Commission
K	Kelvin, unit of Correlated Colour Temperature
LCC	Life Cycle Cost
LED	Light Emitting Diode
LEF	Luminaire Efficiency Factor
LFL	Linear Fluorescent Lamps
LiFi	High-speed wireless communication based on high-frequency LED light modulation
LLMF	Lamp Lumen maintenance Factor
LMF	Luminaire maintenance Factor
LOR	Light Output Ratio
LSF	Lumen Survival Factor
lm	Lumen, SI unit of luminous flux
lux	SI unit of illuminance. 1 lux = 1 lm/m^2.
PIR	Passive InfraRed
Ra	Colour rendering index
RGB	Red Green Blue (referring to colour mixing LED-lamps)
SDCM	Standard Deviation Colour Matching
ta	Rated ambient temperature = highest sustained temperature for normal luminaire operation
tq	Rated quality ambient temperature = highest sustained temperature for a defined level of performance
TCO	Total Cost of Ownership
W	Watt = 1 Joule/second (rate of energy conversion or transfer)

1. Introduction

1.1 The Benefits of LED Lighting

LED lighting technology provides large opportunities for energy efficiency and high quality lighting for both the private and public service sectors. The LED technology is very different from former lighting technologies and holds many possibilities for innovation. This can result in better working conditions and greater well-being e. g. through optimised luminaires, built-in lighting, flexible lighting control, luminaires where the user can change the spectral distribution and colour temperature, mimicking of the outdoor lighting variation over the day, smart lighting and better use of daylight.

The efficacy of good LED solutions is more than 100 lm/W and the efficacy continues to increase year by year. The EU eco-design regulations 244/2009, 245/2009 and 1194/2012 include the LED technology but these regulations were written before the LED technology was mature and reached the present technical level. For the tertiary sector, a labelling scheme for luminaires and lighting systems is currently not available and the national adaption of the Energy Performance of Buildings Directive (EPBD) provides only limited support for the design of energy efficient lighting systems in buildings.

A large part of the indoor lighting systems used in the private and public service sector are still based on inefficient technology in the form of T8 fluorescent tubes with electromagnetic ballasts and halogen lamps. It is beneficial that these technologies are replaced by LED lighting systems with effective control features. In an increasing amount of cases, it is also beneficial to replace T5 fluorescent tubes. In general, it is recommended to change both the luminaire and the lamp(s) instead of conducting retrofit of existing luminaires, which often leads to challenges with change of the lighting distribution.

1.2 Request for Guidelines

The development of LED lighting is ongoing at high speed where new and better products come to market every six months. International standards are still in progress. Many stakeholders have experienced that they came to choose a non-optimal LED lighting system due to lack of information and criteria for selecting the right solution.

Stakeholders within the tertiary sector request guidelines that can support innovative solutions, procurement criteria for selection of high quality efficient LED lighting systems and best practice examples. With the current dynamic development the criteria must be updated regularly, while general recommendations for good lighting design will hold for a longer period.

The guidelines focus on the main areas of application within the service sector including:

- Offices
- Schools
- Museums and exhibitions
- Retail
- Healthcare

2. Lighting Design

2.1 Introduction

Primarily, lighting design serves to provide suitable visual conditions for the building occupants. The goal is to provide "the right light at the right time at the right place" to obtain good:

- Visual conditions to perform tasks even under difficult circumstances and during longer periods
- Visual comfort that provides a sense of well-being and contributes to higher performance

The visual performance for positions/objects in the room depends especially on:

- The **illuminance** which is a measure of the amount of light incident on a surface/plane. The measurement unit is lux.
- The **luminance** which is a measure of the amount of light in a given direction. The measurement unit is candela per square meter (cd/m^2)
- If the object is three-dimensional and/or coloured.

There are many other determinants for good visibility and lighting design. These topics are described in the sections below including:

- Facilitating the visual performance of the eye
- Access of daylight
- Nature of tasks and surface properties of space and objects
- Standards supporting satisfactory visual performance
- The need for general lighting and uniformity
- Relative brightness of the task object compared to the surroundings (contrast)
- Direction of the light
- Attractive lighting of the interior of the building
- Optical guiding lighting systems can improve visibility and ease of navigation
- Variability of the lighting (levels and colour)
- Colour rendering and colour appearance of the light
- Glare and flicker
- Ensure safety and security

2.2 Visual Performance of the Eye

The luminance distribution in the visual field controls the eye's adaptation and thus the task visibility. A well-balanced adaptation luminance is needed to increase:

1 **Visual acuity** (sharpness of vision).

2 **Contrast sensitivity** (discrimination of small relative luminance differences).

3 **Efficiency of the ocular functions** (such as accommodation, convergence, pupillary contraction, eye movements, etc.).

The following types of luminance distribution should be avoided:

- too high luminance which might create glare
- too high luminance contrasts which can cause fatigue due to constant eye re-adaptation
- too low luminance and/or too low luminance contrasts which result in a dull and non-stimulating working environment.

A well-balanced luminance distribution requires evaluation of the luminance of all surfaces (determined by the reflectance and the illuminance). Human visual comfort is obtained by bright interior surfaces, particularly the walls and ceiling, with selection of the appropriate reflectance and illuminance values for the interior surfaces.

The illuminance and its distribution on the task area and on the surrounding area have a great impact on how quickly, safely and comfortably a person perceives and can carry out the visual task. The European standard EN 12464-1 provides values of maintained illuminances that fulfil visual comfort and performance needs (see part 2.5).

Good lighting design also needs to consider the age of the building occupants. As we get older, the lens in the eye loses its flexibility, which reduces our eye accommodation capability leading to the need for reading glasses. With increased age, the vitreous body of the eye becomes polluted by proteins and other substances, which spreads the lighting radiation that hits the eye, leading to a higher sensitivity to glare. As we age, muscles that control our pupil size and reaction to light lose some strength which causes the pupil to become smaller and less responsive to changes in ambient lighting. Because of the reduced light transmission in the eye lens, cornea and vitreous body, we need around three times more ambient light for comfortable reading in our 60s compared to our 20s [17].

Colour perception is also important for the visual performance. For the human eye, some colours are more visible than others. The visual sensitivity of the human eye is at its maximum in the yellow-green region of the spectrum. The contrast between colours is also important and this is improved by good colour rendering properties of the lighting system.

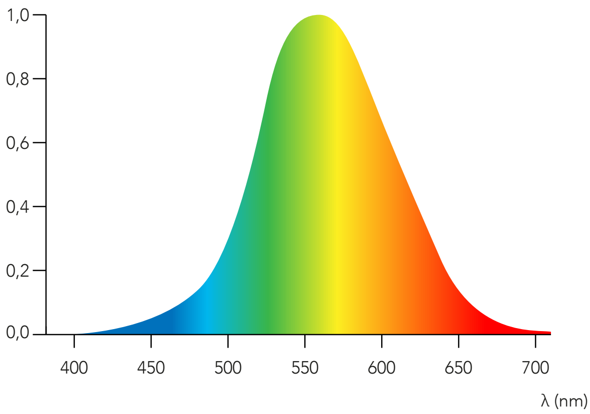


Figure 2 *Relative spectral sensitivity of the human eye under photopic conditions, the so-called V(λ)-curve*

2.3 Daylight

Over thousands of years our eyesight has developed with daylight as the primary lighting source. Over the day and the year the earth movement in relation to the sun provides huge daylight variations in brightness, direction, spectral distribution and colour. Our eyesight has an exceptional ability to adapt to brightness variations from a few lux to more than 100 000 lux.

Daylight should be leveraged as much as possible, when lighting a building's interior. Efficient electric lighting therefore needs to be planned and controlled depending on the access to daylight. The minimum requirements for indoor artificial lighting have to include both day time and night time. The amount of the daylight entering the room depends on the light from the sky, light that reflects in from surrounding buildings, outdoor sun screens and window transmittance.

In a room, the daylight factor D defined for a cloudy sky expresses how much of the daylight reaches a surface or a point in the room. The example in figure 3 shows how in this case with a daylight factor of 5 %, the recommended table illuminance for writing and reading is obtained (for recommended illuminance values please see part 2.5).

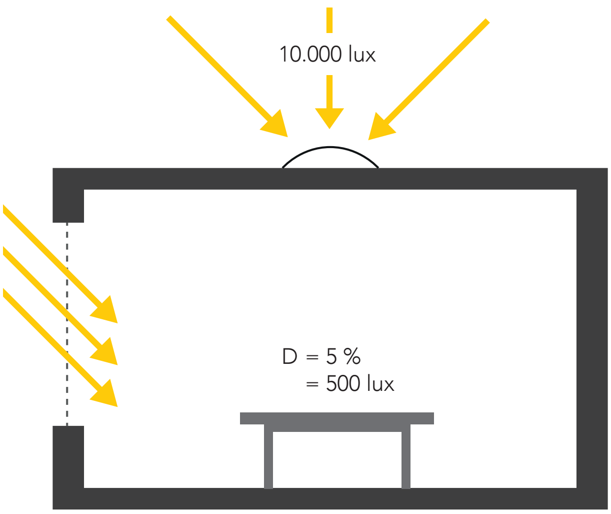


Figure 3 *Example of illuminance from daylight expressed by the daylight factor*

2.4 Different Types of Lighting

Lighting is generally divided into three types [22]:

1 **General lighting** usually consists of **ceiling-mounted luminaires** placed with the same distance between them and half the distance to the wall. General lighting provides the required illuminance all over and complete furnishing flexibility. The overall appearance might not be appealing and energy consumption is higher than for the next two types of lighting as the lighting is not adapted to different needs in the room.

2 **Localised lighting** consists of **ceiling-mounted luminaires at each work station** that provide the necessary task illuminance plus sufficient broad light distribution for walking areas. Compared to general lighting, the energy consumption is lower but there is reduced flexibility in placing the work stations. Localised lighting also includes decorative lighting e. g. to display architectural details and paintings.

3 **Local lighting** includes lighting that can be **moved around along with work stations** plus general lighting for walking areas. The benefits are: 1) flexible placement of work stations, 2) better energy efficiency than for solely general lighting, and 3) the staff can control all their own lighting (some of the localised lighting might be shared by workers). Local lighting can refer to table lamps, up-lighters and built into furniture where LED lighting is suitable due to the smaller size.

Many lighting installations are of the general lighting type which allows for flexibility in positioning work stations but the energy consumption is typically higher than that of localised or local lighting.

Moreover, studies have shown [26] that in terms of user performance and preference, lighting with a certain degree of non-uniformity is more effective. Pendant LED luminaires with adjustable and typically lower luminous flux can be used to obtain energy savings as this reduces the need for general lighting [27].

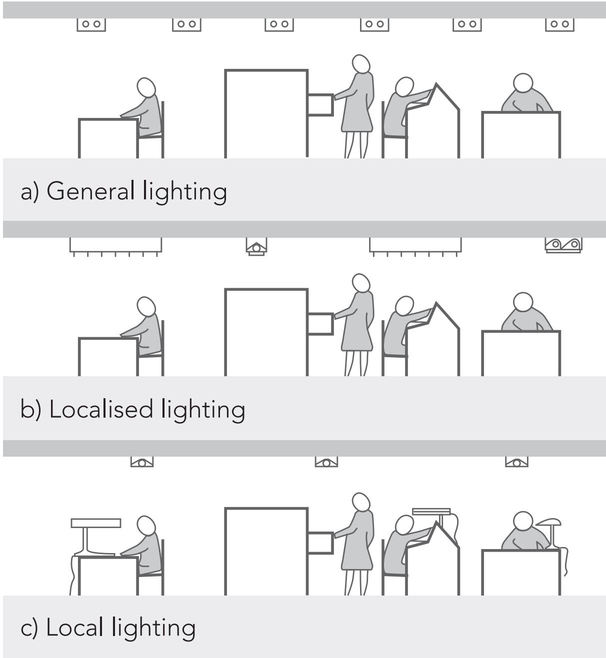


Figure 4 *Types of interior lighting*

2.5 Illuminance for Indoor Work Places and Applications

The standard "EN12464-1:2011, Light and lighting – Lighting of workplaces – Part 1: Indoor work places" specifies recommendations for lighting solutions in most indoor work places, in terms of quantity and quality of illumination for people with normal visual capacity. This standard is relevant and applicable across the EU.

The standard includes lighting requirements for different types of work, the kind of visual task including use of DSE (Display Screen Equipment), plus duration of the activity. Recommendations are also given for good lighting practice related to safety and health.

The specified average illuminances for a specific lighting task have a strong influence on the lighting design.

The standard makes a distinction between the work/task area, the immediate surrounding area (at least a width of 0.5 m around the task area) and the background area (at least 3 m width adjacent to the immediate area). It is recommended the illuminance ratios between working area, immediate surroundings and background illuminances are in a ratio of 5 : 3 : 1.

Table 1 *Extract of recommended requirements for indoor lighting*

Type of area, task and activity	Maintained average illuminance for task area (lx)	Maximum Glare (UGR_L)	Minimum illuminance uniformity (U_O)	CRI (Ra)
Office: Writing, reading, data processing	500	19	0.40	80
Office: Reception desk	300	22	0.60	80
Retail premises: Sales area	300	22	0.40	80
Public assembly: Entrance halls	100	22	0.40	80
Public assembly: Corridors	100	25	0.40	80
Public assembly: Conference rooms	500	19	0.60	80
Educational buildings: Classrooms	300	19	0.60	80
Educational buildings: Adults education	500	19	0.60	80
Educational buildings: Technical drawing	750	16	0.70	80
Health care: Wards general lighting	100	19	0.40	80
Health care: Examination and treatment	1000	19	0.70	90

UGR_L, U_O and CRI are explained in the following sections.

The illuminance defines the amount of light falling on a surface and is measured in lux. EN12464-1 includes tables with detailed illuminance requirements for nearly all kinds of interior areas, tasks and activities. Some examples are given in table 1.

In case the work area is yet not defined or the building owner wants flexibility, the designer can choose between 1) the best illuminance in the work area or 2) provide the workstations with task lighting and have basic lighting in the rest of the area.

2.6 Lighting Uniformity

Lighting uniformity refers to the evenness of illumination across the work area, floor and walls respectively. Uniform lighting is particularly important for work areas. If the lighting is uneven, the eyes of the occupants make involuntary adjustments for the different lighting levels while trying to stay in focus, creating undue stress and fatigue.

The standard EN12464-1 specifies an additional design criterion to discourage excessive non-uniformity. In purely mathematical terms, lighting uniformity is the ratio of minimum to average illumination for a given area. The minimum illuminance uniformity is called U_O. In the case where the uniformity requirement U_O is 0.6 and the illuminance requirement for the work area is 300 lux, the illuminance at any point in the work area will be a minimum of 180 lux.

The daylight distribution in a room with windows will normally be rather uneven which can be perceived as stimulating and positive as long as it does not reduce the comfort and the ability to read boards or screens. In case of uneven distribution, sun screening might be used to control lighting uniformity.

The main direction of the light affects our ability to see the depth, form and texture of an object or person and thus influences our capability to estimate the distance. The total directionality of incident light is very important when three-dimensional objects need to be recognised as such.

Uniform lighting coming from "all" directions, such as indirect lighting, does not produce shades and as a result, makes visible objects look flat. This kind of lighting is called diffuse lighting. Direct lighting causes shadows and can cause details to disappear. In general, **the best lighting is a mix of diffuse and direct lighting.**

Designers can choose from a variety of reflector types for LED illumination with different reflector forms, reflector colours, and lamp position; all impacting light evenness. Furthermore, lenses can be used to achieve different light qualities e. g. frosted lenses create more uniform illumination but decrease the brightness. It is important to weigh up all the options before committing to a lighting choice.

2.7 Luminance Contrast

Luminance contrast is a photometric term determined by the difference in the colour and brightness of an object compared to its background within the same field of view. A lighting design that brightens some objects while others stay shaded can provide improved visibility.

Many lighting professionals recommend a maximum ratio of 5:1 or lower between general and task lighting, and a maximum ratio of 10:1 between hallways and other "traffic" areas.

The luminance distribution in a room is determined by the windows, the position of the luminaires, the light distribution and the reflective surfaces in the room. A well balanced luminance distribution increases visual acuity and contrast sensitivity.

Generally, **good contrast and colour selection is preferable to a very high illuminance** because the human visual system is more sensitive to contrast than high illuminance. Luminaires can be directed towards working areas, the lecturer, a sign or other important subjects without increasing the general lighting. **The benefits of good contrast are: increased visual impression (provided no glare) and low energy consumption.**

Lighting can also cause interfering reflections on computer screens. The standard EN12464-1 specifies average luminance limits for luminaires, to avoid reflection onto flat screens. The limits are specified for elevation angles of 65° and above and are typically <1000 cd/m² or 1500 cd/m². For critical computer screen activities this starts from 55° all around.

2.8 Glare and Photo-biological Safety

Glare appears in the case of very high luminance or large luminance contrast often due to lack of shielding from a window, reflection or from direct sight of the LED light sources in the luminaire. Normally, the eye adapts to any lighting situation, but if the lighting of the object or its background is too bright or the contrast is too great, vision suffers by glare. **There are two types of glare:**

- **Disability glare**, which affects the ability to see and is produced by high luminances in a low luminance scene, typically by point light sources such as bright spotlights aiming at the observers eye, or by large area sources such as a bright LED panel.
- **Discomfort glare**, which appears in the form of visual discomfort without affecting the ability to see. Discomfort glare is quantified by the Unified Glare Rate limit values (UGRL) ranging from UGRL 10 (not noticeable) over UGRL 16 (unpleasant) to UGRL 28 (terrible). The standard EN12464-1 recommends UGR limits for specific types of rooms and applications (see table 1). Discomfort glare can cause an ergonomically incorrect sitting position (in an attempt to avoid the glare), fatigue and headaches.

The standard EN12464-1 also specifies minimum shielding angle in all directions depending on the lamp luminance. For indoor installations disability glare is rare while discomfort glare might often appear.

With the small size of LED lights and their corresponding brightness, it is recommended to be aware that glare may appear or even cause eye injury if users look directly at the LED light source for a long time.

Glare can be avoided by:

- Lighting design without sharp transitions/contrast
- Control of the light from windows (e.g. with blinds or thin curtains)
- Providing the building with a fixed shield for high sun
- Manual control of the window shields (e.g. many people want to see the sunlight on a winter day)
- Installation of reflective or absorbent glazing on windows. Coloured glass should be avoided because it reduces light in cloudy weather periods
- Bright ceilings, panels and walls (e.g. provided by up-lighting with good light distribution)
- Use of soft diffused lighting in rooms with data screens
- Lighting directed at working areas
- Use of larger light sources with less light concentration
- Partial use of up-lighting
- Use of diffusers and shutters in luminaires
- Shielding of lamps from the eyes at normal viewing angles with even light distribution
- In case of doubt about glare from a lamp, a small mirror might be placed in the working and the lamp moved until it is no longer visible in the mirror

Blue light hazard is a photo-biological safety concern that occurs when blue light rays penetrate the cornea and are directed onto the retina by the lens. According to current experience, no light sources that emit white light used in general lighting applications are

considered hazardous to the retina for healthy adults, however special lamps e. g. lamps with high light intensity in the blue spectrum must be considered on a case-by-case basis. Light sources used by sensitive persons e. g. infants or adults with certain types of eye disease, require additional evaluation.

The standards IEC 62471/CIE S009 and IEC/TR 62778:2014: Application of IEC 62471 specify four Risk Groups (RGs) [13]. In order to ensure the photo-biological optical safety, it is recommended LED lamps and luminaires fall in RG0 or RG1 [1].

2.9 Colour Temperature and Tolerance

LED lighting systems can be provided with a range of different Correlated Colour Temperatures (CCTs):

- **Warm yellowish white** (2700 – 3000 K) which creates an intimate ambience suitable for domestic settings, and where desired in bars, cafes or restaurants.
- **Neutral white** (around 4000 K) which is good for working environments as this CCT boosts productivity.
- **Cool bluish white** (around 6500 K and beyond) where artificial lighting mixes with daylighting.

The choice of an appropriate colour appearance of a light source is largely determined by the function of the room being lit. Research has indicated that a high CCT is preferred at higher lighting levels. A high CCT is also preferred in warmer climates, while in cooler climates and in the absence of daylight a lower CCT (warm appearance) is preferred.

When LED chips are manufactured, tolerances occur which can result in differences in light colour. Care should be taken to ensure small colour differences – especially for lighting applications where individual light sources are not far apart and can be seen simultaneously. LEDs are therefore tested after they are manufactured and sorted into tolerance classes. This process is called "colour binning". A colour bin (MacAdam ellipse) corresponds to a particular area of the CIE chromaticity diagram. Most people would not see any difference in the colour within a one-step MacAdam ellipse. Some colour differences are only noticed with a two-step MacAdam ellipse, which is currently considered as good practice in LED lighting [9].

The standard ANSI C78.377: 2015 "Specifications for the Chromaticity of Solid State Lighting Products" recommends selecting nominal CCTs specified by chromaticity quadrangles and Duv tolerances (see table 2 in chapter 5). Technically, the chromaticity tolerance is the distance of a light's chromaticity from the Planckian (black body) locus and target CCT. This method is also recommended by IEA 4E SSL [1] because the alternative method with use of MacAdam steps (ellipses refer to regions on the CIE Chromaticity Diagram) is harder to measure in the laboratory and is a less detailed measure.

LED lighting with control is capable of providing variations in luminance and "tuning" the correlated colour temperature. The best systems are able to provide the same variation as the natural lighting cycle. Advice about this kind of control is provided in chapter 4.

2.10 Colour Rendering

Colour rendering defines the ability of a white light source to render object colours accurately. It is expressed by the general colour rendering index (CRI) with values from 0 to 100, where 100 is the best (100 is provided by daylighting). Excellent colour rendering is achieved by lamps with a CRI above 90 which is e. g. needed in clinical areas in hospitals, health care buildings, museums, theatres, colour inspection/control/selection and some types of retailers. In general, a CRI above 80 is considered sufficient for accurate colour judgement in most indoor spaces.

The standard EN12464-1 specifies minimum colour rendering requirements for practically all kinds of tasks by CRI (Ra). Table 1 shows concrete information on what CRI levels are recommended with minimum CRI 80 for nearly all types of rooms and applications except CRI 90 for health care examination and treatment.

The CRI is defined by CIE as the average of the colour rendering indexes for eight test colours with low chromatic saturation. However there are 15 colour indexes. LED research has found that the index R9 (for the red colour) is very important for LED lamp colour rendering. It is recommended to use the IEA 4E SSL [1] requirement of R9 > 0. Generally in lighting design, it is important to be aware that the colour rendering provided by the light source may be reduced by optics, glazing and coloured surfaces.

2.11 Lifetime

High-quality LEDs can maintain their light output for tens of thousands of hours. The built-in electronic driver, however, may show a sudden failure so the lifetime of the whole lighting system has to be considered.

The LED lamp lifetime is defined as the period during which a given fraction of the total number of lamps (By) provide more than a pre-defined percentage of the rated luminous flux (lx), under standard test conditions, e. g. $L_{70}B_{50}$ > 25,000 hours means that no more than 50 % of the lamps give less than 70 % of the rated luminous flux after they have been used for 25,000 hours.

Rated lifetime should be balanced with price considerations, bearing in mind that for LED light sources with a very long rated lifetime, it may be profitable to replace them before the end of their life cycle with new LED products with substantially higher efficiency – currently new, more energy efficient LED products appear on the market every six months.

2.12 Ambient Temperature

LED luminaire performance is influenced by the ambient temperature. The rated ambient temperature (t_a) is the highest sustained temperature at which the luminaire may be operated under normal conditions.

Temperature t_q (quality) indicates the highest rated ambient temperature permitted for a defined level of performance (incl. rated lifetime and lighting characteristics). More than one t_q value can be declared for different performance characteristics.

Where t_a = 25 °C, no declaration is required for the luminaire; any other rated ambient temperature value needs to be declared (the same rule applies to t_q) [14]. Due to summer heat and still air around ceiling level, the ambient temperature might in some periods be around 30 °C for some applications. For this reason, some Danish municipalities in general procure for the ambient temperature 30 °C.

2.13 Maintenance

In new installations, all the surfaces of luminaires are clean, the lamps emit the full luminous flux and the surface of the luminaire and the room have optimal reflection properties.

As time passes, dirt gathers on luminaires and on room surfaces. With age, lamp efficiency deteriorates and plastic diffusers, prismatic controllers and reflectors become discoloured. Luminaire depreciation is affected by the cleanliness of the environment and the design of the luminaire, e. g. uplighters are more sensitive to dirt depreciation than downlighters.

In particular the degree of protection against the appearance of dirt on the luminaire is important. After 3 years, luminaire dirt depreciation can range from 10 % reduced light output in enclosed fixtures that are located in clean environments to more than 60 % in open fixtures that are located in dirty areas [28].

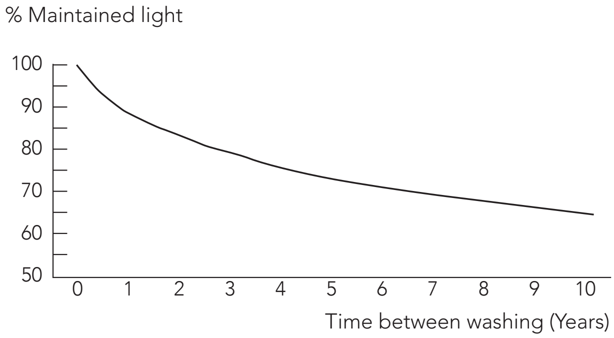


Figure 5 *Example of expected loss of light resulting from dirt build-up for enclosed troffers in a clean office environment*

EN12464-1 prescribes that in the development of a lighting solution a maintenance factor needs to be used to compensate for light reductions. The maintenance factor has a great impact on energy efficiency and depends on the maintenance characteristics of the lamp and control gear, the luminaire, the environment and the maintenance programme.

The output of a luminaire after a given elapsed time, specified as a fraction of output when the luminaire is clean, is known as the **luminaire maintenance factor (LMF).**

The relative lamp output after a specific number of burning hours is known as the **lamp lumen maintenance factor (LLMF).**

Lighting installations are designed on the basis of required illuminance level for specific application stated in standards and recommendations. An adequate illuminance value is chosen to ensure the minimum illumination is provided during the lamp's full lifetime. Maintenance of many lighting installations is often poor, which has often caused designers to use lamp lumen depreciation factors of 20–30 %.

However, at the beginning of the maintenance cycle when the lighting output is above the requirements, excess lighting might be limited by use of dimmers and this will save energy.

Another solution is to select a LED lamp/luminaire product with luminous flux constant over its lifetime by regulation of the driver current.

Cleaning of LED luminaires should be performed at pre-determined regular intervals in accordance with the manufacturer's requirements, the immediate environment conditions and the IP rating of the luminaire. Lighting measurements should be carried out in connection with cleaning.

2.14 Safety

The LED lighting products must be safe when installed, in use and when they reach the end of their life.

A key criterion for specifying and selecting LED lighting products and systems is to ensure they are CE marked as required for sales at the EU internal market.

IEC safety standards have become mandatory EN safety requirements in the EU including EN 60061, EN 60598, EN 61347, EN 62031, EN 62471, EN 62560 and EN 62663-1. These are included within a number of EU Directives including Low Voltage, Electromagnetic Compatibility (EMC) and Ecodesign requirements, whereby compliance is indicated on LED system products via the CE marking.

To help ensure compatibility, future availability and support, IET UK [9] recommends that designers and installers investigate their supply chain and use reputable firms who are able to demonstrate a responsible approach to quality, product availability, ongoing support and warranties.

It should be verified that CE Declarations of Conformity and test sheets are provided for the correct product and type of product. It is recommended that formal copies of the CE certification documents are requested and obtained for all LED products owing to a number of counterfeit CE marked goods currently in circulation.

Added confidence can also be secured by requesting that the manufacturer provides results from third-party independent testing of their products.

3. Energy Efficiency and Life Cycle Costs

Besides designing a lighting system with the right lighting quality it is also important to select the most energy efficient system.

This chapter includes sections about:

- Efficacy of the total lighting system,
- Luminaire retrofit
- Shift to new LED luminaires
- Life cycle cost and payback period

3.1 Total Lighting System

In this report, "Total Lighting System" is defined as the luminaire, light sources and driver/ballast (also called control gear) where different types of lighting control might be added. However in some other contexts, such as EU DG ENER Lot 37 preparatory study [25], "Lighting System" also includes the geometric arrangement and the room with reflectance of walls, ceiling etc.

A traditional luminaire includes the components:

1 **Housing,** also called **troffer** that contains all parts and the **ballast/driver,** if this isn't directly integrated in the lamps (typically the case for LED lamps in the tertiary sector).

2 **Reflector** to direct the light in the desired direction.

3 **Lamps** (also known as light sources) and their respective lamp holder or socket.

4 **Shielding** (lens, louver, or similar) to reduce discomfort glare and often also to control the distribution of the light output.

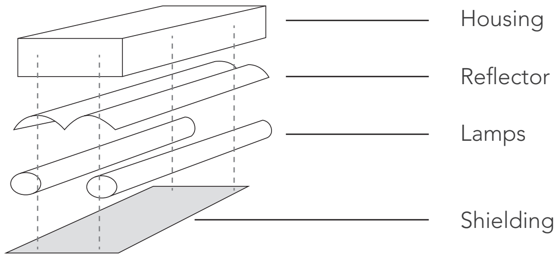


Figure 6 *Luminaire construction*

The efficiency of a luminaire depends on:

LOR = Lumen Output Ratio
= Total lumens emitted by the luminaire/ Total lamp lumen output

LOR might be detailed by ULOR (Upper Light Output Ratio) and DLOR (Downward Light Output Ratio).

The efficacy for the total lighting system is defined by:

LEF = Luminaire Efficiency Factor
= Light source efficacy * LOR * Driver efficiency

The LEF unit is lm/W.

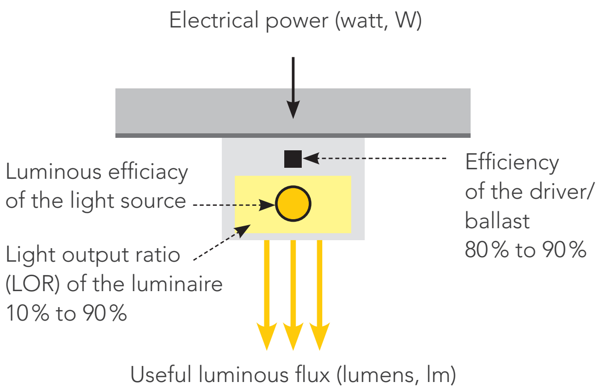


Figure 7 *Total lighting system efficacy and useful luminous flux*

In some contexts LEF is named Luminaire (Luminous) Efficacy [lm/W] with the symbol: η_L

For task lighting, it is not enough only to consider the LEF. It is also necessary to consider the luminous intensity distribution from the luminaire e. g. a naked omnidirectional LED-lamp or module with LOR 100 % might provide much lower illuminance on a target area than a well suited luminaire with LOR 80 %.

For new buildings or installation of a new lighting system different efficiency requirements are set. The most common requirements are:

- **Maximum W/m²** for design of new installations including lamps, ballast/drivers and control gear (still in accordance with illuminance levels in EN 12464-1:2011) [3, 6].
- **Maximum kWh/m² per year** using the methodology and energy consumption criteria in standard "EN 15193 Energy performance for buildings – Energy requirements for lighting" including the Lighting Energy Numeric Indicator (LENI) with unit kWh/m², year. Some countries have national regulation that relates the requirements to the operation time e. g. Poland. In case the annual operating hours are unknown, EN 15193 Annex G provides default values relating to building types.

3.2 Retrofit of Fluorescent Tube Luminaires

Fluorescent tubes with electromagnetic ballasts may be retrofitted with double-ended LED lamps if the manufacturer of the retrofit LED lamps provides instructions and a declaration taking responsibility for the safety and performance of combined luminaire and retrofit lamps. According to this instruction the existing starter may need to be replaced or removed. Depending on the instruction and the national safety requirements, it may not be required for the work to be done by an electrician.

In the case that a luminaire including fluorescent tubes with electromagnetic ballast also needs to undergo technical modification (conversion), e. g. in the form of replacement or modification of control gear and/or internal wiring, these alterations need to be performed by an electrician, ensuring that they comply with the relevant safety and operating standards and meet the necessary electromagnetic compatibility requirements. In such a case the original CE mark must be removed and be replaced with a new CE mark.

For this kind of retrofit, the lighting distribution is changed. Compared to the flux from the fluorescent tube, the LED retrofit tube typically only emits 50 – 60 % with radiation in a smaller beam angle such as 135 – 160°, whereas the fluorescent tube radiates in 360°. Depending on the luminaire, the installation geometry and the application, the smaller beam angle of the LED tube typically compensates for the smaller flux directed under the luminaire with provision of the required amount of lighting. In any case, there might be other problems with an LED retrofit e. g. heat in the luminaire and/or the original light calculation is no longer applicable, as the luminaire geometry and reflector only provides optimal light distribution and reflectance in the room when the fluorescent tube is used.

In case the outer lighting distribution from the luminaire is important, the LED retrofit solution is often not acceptable as the client might experience black spots in the room with too little lighting. This could be compensated by moving the luminaires as well as installing extra luminaires, however the economic case for this kind of retrofit is most probably no longer competitive.

In general, it is recommended to retrofit both the luminaire and the lighting source following the advice provided in the next subsection. This solution will provide the greatest energy savings due to use of a dedicated LED luminaire that provides optimal light distribution and reflectance in the room for the LED light source. This solution also opens up for the many LED lighting control options.

3.3 LED Luminaire Selection

Aiming at both good lighting quality and high energy efficiency selection of the LED luminaires, the installer has to consider a number of parameters:

- Appearance
- Necessary light distribution
- Is there a need for a combination of direct and indirect lighting?
- Is there a need to direct the light by reflectors?
- Selecting the appropriate type of luminaire providing glare control, light distribution and illuminance (lux) and being as energy efficient as possible.
- Is there a need for lighting control and which types of controls are needed?
- Ease of maintenance including resistance to dirt, cleaning, exchange of components, modular design and repair.

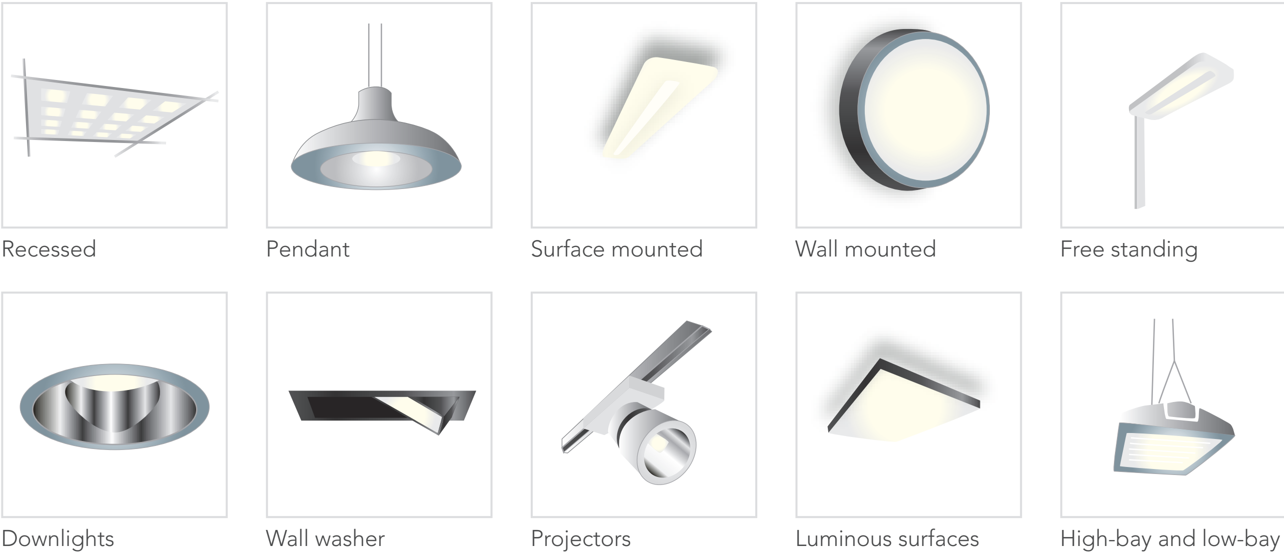


Figure 8 *Different types of indoor luminaires*

3.4 Life Cycle Cost and Payback Period

The often large investment for LED lighting systems should whenever possible be justified by a Life Cycle Cost (LCC) calculation.

LCC = Investment (lighting design, lighting system, control, installation)
+ operation (electricity consumption)
+ maintenance (cleaning and replacing lighting sources and/or driver)
− energy saving grant

LCC =

$$n \times (C_L + C_I) + \frac{(n \times h \times P_L \times C_E)}{1000} + a \times n \times \frac{L_P}{L_L} \times C_{m1} + C_{m2} - W \times C_T$$

- n Number of luminaires
- C_L Price of luminaire including light sources
- C_I Price of installation per luminaire
- P_L Wattage per luminaire including light source(s) and driver/ballast
- C_E Electricity price
- C_T Energy saving grant per kWh
- W Yearly electricity saving compared to the former lighting system
- h Operation hours per year
- a Constant with value "1" if $L_L < L_P$ or else value "0"
- L_L Lifetime for the light source
- L_P Lifetime for the project (typically the lifetime for the new LED light source)
- C_{m1} Cost for replacing light sources in the luminaire
- C_{m2} Other maintenance costs in the project lifetime

The purchasing costs are typically higher for the LED lighting system when compared to traditional lighting systems, while the operation and maintenance costs are lower. An LCC assessment approach can justify the initial investment costs when considering the costs and savings over the lifetime of the lighting system. LCC calculations shall include parameters such as cost of labour, energy costs, purchase price, expected life time of luminaires, maintenance costs (group cleaning of a luminaire, luminaire repair, frequency of luminaire cleaning etc.).

For a LED retrofit project, calculation of the simple payback period is an often sufficient measure of the life cycle cost:

$$\textbf{Simple payback period (years)} = \frac{\Delta IC}{\Delta OC + \frac{\Delta MC}{L_P / H}}$$

- ΔIC Difference in investment costs
- ΔOC Difference in yearly operation costs
- ΔMC Difference in maintenance costs in the project lifetime
- L_P Lifetime for the project
- h Operation hours per year
- (L_P / H) Project lifetime in years

The simple payback period does not include the yearly interest rate, which is a weakness if the interest rate is high and/or the project lifetime is more than 5 years.

The discounted payback period can be calculated by summarising the discounted savings. The year when the summarised discounted savings are equal to ΔIC is the payback period.

Discounted saving = yearly saving / $(1+i)^n$

i Discount rate
n year in the project lifetime

Alternatively the life cycle cost can be calculated by using for example one of the following approaches:

1 **The net present value method** as specified by the CIE 115:2010 Technical Report, p. 24 [CIE] including use of the discounted value of the annual savings

2 **The average annual costs method** as specified by the CIE 115:2010 Technical Report, p. 24. [CIE]

3 **The method specified by Requirement ID:10677:1** of the Swedish National Agency for Public Procurement (Uphandlings myndigheten). [UM]

4. Lighting Control

Lighting accounts for a large part of the electricity consumption in the service sector. The operation time for lighting is often long and constant. Implementation of different types of lighting control is beneficial as it can lead to large energy savings. Information and guidance are provided below concerning control strategy, use of daylight, different types of controls and sensors, LED capability, smart lighting and human centric lighting.

4.1 Selection of a Control Strategy

Lighting control can be provided by:
- Manual control using localised switches and dimmers
- Automatic control using timers, occupancy and photoelectric daylight sensors
- A combination of manual and automatic control

Figure 9 provides a method for selecting a control strategy with four steps, checking the following aspects of the initial situation and the type of use of the building and room [21]:

1. Availability of daylight
2. Occupancy pattern
3. Number of occupants
4. Type of occupation including:
   - Variable occupation where occupants spend only some of their time in the space
   - Scheduled, intermittent and relatively short stays (e. g. school classroom)
   - Full occupation where occupants are in the space for the entire working day
   - Intermittent occupation of an area visited only occasionally for short periods

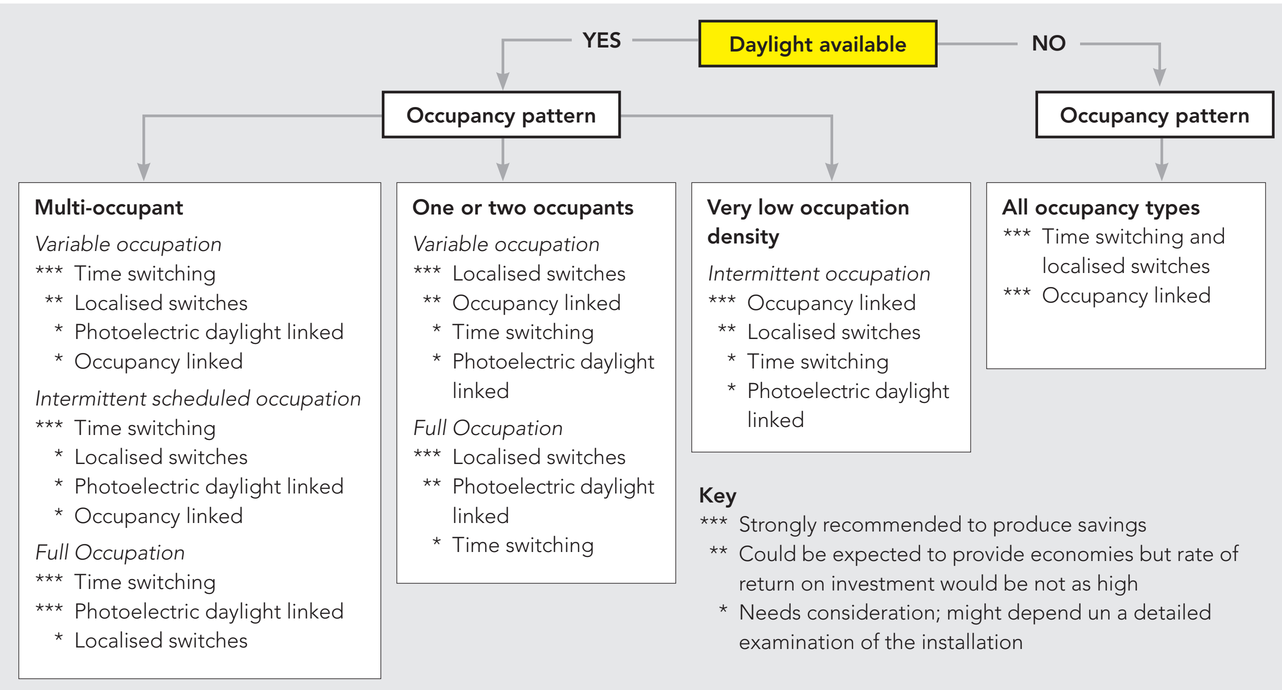


Figure 9 *Selection of a control strategy*

4.2 Use of Daylight

Daylight is considered refreshing, providing better lighting quality than artificial light and more comfortable colours due to the continuously changing luminance level, direction and spectral composition of the daylight [32]. Daylight creates healthier interiors (see section 4.4 about human centric lighting) and more wellbeing for the occupants leading to higher work performance and productivity [31].

The energy saving potential of using daylight for illumination in buildings depends on the building architecture (e. g. the size of the windows and the light transmission through the glass type), surrounding buildings and vegetation, geographic latitude and meteorological conditions.

Windows are often strongly favoured for the daylight and visual contact they provide with the outside. However, it is important to ensure windows do not cause visual discomfort (glare), thermal discomfort [30], or a loss of privacy. To overcome these pitfalls, opportunities to leverage daylight should be taken into account at the early stage of the building design.

An integrated approach that takes into account both the building envelope and lighting system provides increased energy savings and improved comfort compared to conventional non-integrated practice. Architects responsible for the shell of the building often neglect to explore the full integration of daylight opportunities with their lighting system consultants [15 and 16].

In new buildings, it is important to align the design of both the building envelope and lighting system in order to leverage optimal use of daylight and achieve energy savings and comfort.

Realisation of full energy saving potential by leveraging daylight requires good control of the artificial lighting. Often quite simple control systems are quite effective. Studies have shown [35] that an occupant would be more likely to switch lights on when entering from a brighter space than when entering from a dark space. Since manual switching is the most common form of lighting control, a simple way to save lighting energy might be to ensure that the illuminance in corridors is substantially less than in rooms where the work is taking place.

Some countries have national regulation that requires daylight control, e. g. the Danish Building Regulation [24] requires that in cases where there is sufficient daylight, work rooms (offices etc.) and access areas (e. g. corridors) have to be provided with **automatic daylight control**.

Conventional vertical windows are the most common daylight providing concept. For most visual tasks in commercial buildings, a window surface of approximately 20 % of the floor area will provide adequate daylight to a depth of approximately 1.5 times the room height [21].

The practice of maximising window areas often prevails as a solution to increase capacity of daylighting. However, this practice can counteract the energy saving capabilities of daylighting by creating highly different luminance ratios within the space, consequently requiring more artificial light to balance the lighting environment [21] or complex systems to redirect the light such as light shelves, light directing blinds [36], reflective and/or structured ceilings [38]. In conclusion, **too large a window surface may lead to the need for light directing blinds and structured ceilings**.

In spaces with side windows the lighting must be controlled in rows parallel to the windows, so the rows can be switched on/off individually.

Simple daylight systems (e. g. roof and facade operators) often perform better than advanced facade systems attempting to direct diffuse daylight deep into the building through the addition of reflective surfaces [30].

Performance of daylight systems varies depending on maintenance and durability of components. Dust, condensation, or surface deterioration can quickly reduce the optical efficiency, sometimes by more than 50 % [30].

The use of a horizontal skylight provides approximately three times the amount of daylight as a vertical window of the same size [21]. Skylights can be placed closer to the centre of an area and therefore offer more uniform light distribution throughout the space. However, horizontal skylights collect more light and heat in summer than in winter which generally opposes desired conditions. Consequently, vertical or near vertical skylights, such as clerestories and roof monitors, are most often used.

Vertical or near vertical skylights designed according to the zenith angle of the sun can regulate the amount of daylight by obstructing the direct sunlight in the summer, and admitting and reflecting sunlight into the space in the winter.

Light ducts provide interior lighting by collecting sunlight through heliostats, concentrating the light through mirrors or lenses, and redirecting it to virtually any space throughout the building through shafts or fibre optic cables. Additionally, light ducts are highly advantageous considering they transmit light without the transmission of heat [21] [31].

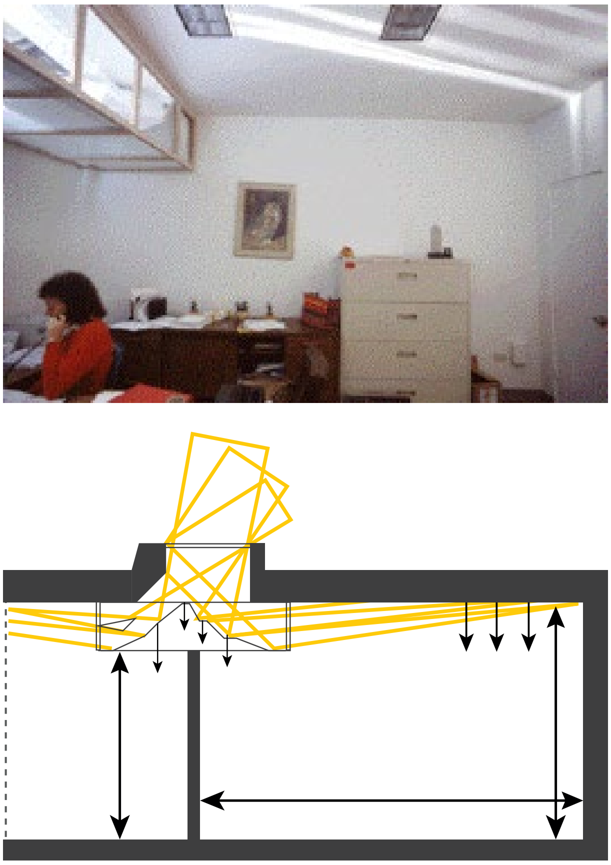


Figure 10 *Example of a skylight that splits and redirects incoming daylight to the ceiling plane in two separate windowless internal offices [33]*

4.3 Manual Control

In areas with high occupancy, localised switching with variable lighting levels is generally desired. Studies in open plan offices have shown wide variations in user preference for lighting with some occupants switching their lighting on under almost all conditions and others doing so only when it is really necessary.

Individual control typically results in noticeably larger energy savings compared to central control of the entire space with only one switch.

Localised switching can be implemented in a variety of ways with varying degrees of complexity and technicality:

- Manual control
- Hand held infra-red remote controls
- Control through an internal network linked to a central control system [18].

Ease of use and the speed of operation affect the way the occupants use the controls, e. g. where controls are difficult to use, occupants may choose lighting conditions, which minimise the need for control use and are usually a high illuminance level.

Concerning the control of luminaires in groups, a rule of thumb is the number of switches in a space should be not less than the square root of the number of luminaires. Thus 16 luminaires would require at least 4 switches.

4.4 Automatic Control

Automatic lighting controls – with manual overrides – offer major opportunities for improving performance, occupant's satisfaction, and energy efficiency.

However, systems sometimes perform disappointingly because insufficient attention has been given to how people react to and make use of the control options [32] [37]. Problems frequently arise because the technology itself had been considered as the solution, without sufficient understanding or analysis of how management, occupants, visitors, and other users (such as cleaning staff) would react to it and use it.

A BRE study [34] indicated that high user satisfaction and high efficiency are generally associated with installation of a high level of local control, high awareness of the controls and ease of use.

There are three main ways to implement automatic control:

1 **Centralised control systems** (bus-based lighting control systems) aim at regulating the light in several rooms, a floor or an entire building. Luminaires, sensors, and computers are connected by a network. A dedicated computer or a building management

system controls the luminaires. Switching and/or dimming can be related to time, daylight, and occupancy. Luminaires can be linked into groups or controlled in particular sequences. The length of time a luminaire is on can be monitored which provides important management information about energy consumption and maintenance. For safety reasons, the emergency lighting installations must not be included in a centralised control system for a building [29].

2 **Stand-alone control systems** are similar to the centralised systems, but they are dedicated to the control of the lighting of one room or even parts of a room.

3 **Intelligent luminaires** have their own control sensors that can signal switching or dimming. The control can be overridden with a hand-held infrared controller. The luminaires can be programmed to provide a constant maintained illuminance throughout the maintenance cycle of the installation. Illuminance level and time delay, which operates when the occupancy sensor ceases to record movement, can be adjusted manually by using controls within the luminaire or remotely.

4.5 Time Switching Control

There are two types of time switching control:

1 Time switching where the lights are programmed to switch off after being **on for a specified amount of time**. This is particularly effective for spaces where unused light is frequently left on, such as rest rooms, closets, and corridors.

2 Time switching where the light system is programmed to provide lighting through **designated periods**, switching lights off during lunch breaks and at the end of the working day. The extinguished lighting can be reactivated manually.

Time switch control is especially beneficial for switching off the lighting at fixed times when the space becomes unoccupied (for example in a museum or other building with fixed opening hours), at night or at the weekend.

Time delay switching is **useful where lighting is only needed for a set period of time**, for example when viewing a display.

4.6 Occupancy Sensor Linked Control

Wisely applied, occupancy sensors can achieve large savings by making sure that lights are turned off in unoccupied rooms. The most appropriate applications for occupancy sensors are in spaces where occupancy patterns are:

- **Intermittent:** toilets, hallways, staircases, corridors, storage rooms and cellars
- **Unpredictable** (otherwise time-switching should be used): cell offices, meeting and conference rooms, school classrooms, laboratories

Occupancy sensors are motion-sensing devices that perform three primary functions:

- Turn the lights on when a room is entered
- Keep the lights on while a room is occupied
- Turn the lights off when a room is unoccupied. This type of control is often very beneficial as it ensures the lighting is switched off at night and at the weekend.

There are three types of occupancy sensors:

1 **PIR (Passive InfraRed) occupancy sensors** that operate by responding to the motion of infrared energy (or heat) produced by human bodies.

2 **Ultrasonic occupancy sensors** that operate by responding to the change in reflected sound waves in a space caused by a moving object. They do not require a direct line-of-sight to detect motion, unlike passive infrared sensors as they detect smaller motions. Ultrasonic sensors operate at frequencies above human sensitivity (20 kHz); typical operating frequencies are 25, 30, and 40 kHz [11].

3 **Dual technology (hybrid) occupancy sensors** combine PIR and ultrasonic technology. They keep lights on if one of the two technologies detects motion, and turn lights off only if neither technology detects motion (or the other way round). These products are more user-friendly as they reduce the likelihood of luminaires turning off while a space is occupied.

Occupancy sensors are available with a variety of manual and/or automatic control options:

- **Automatic-on/automatic-off sensors** are commonly used. They switch the light on when motion is detected and switch it off when no motion is detected. The switch off normally occurs with a delay from the last detection of occupancy. The delay should be

adjusted according to the application of the room, i. e. short for corridors, medium for toilets and longer for offices. These products are appropriate when automatic control with no manual override is desired.

- **Manual-on/manual-off/automatic-off sensors** are switched on manually. The sensors automatically turn off the luminaires when motion is no longer detected if the occupant does not manually turn off the luminaires. These products are appropriate when the occupant sometimes chooses to leave the luminaires off when daylight is adequate or when the occupant desires to maintain the control.
- **Two-level-on/automatic-off sensors** provide control similar to a two-level switching arrangement with separate switch off of lamps within a luminaire or separate switching individual luminaires. The user has the option to manually select either ”half-on” or “full-on” setting on the sensor.
- **Manual-on/automatic-off dimmers** that operate in a manner similar to the manual-on/automatic-off sensors, except they incorporate a slide dimmer.

Occupancy sensors with PIR and ultrasonic sensors are available with two categories of mounting:

- **Ceiling-mounted sensors** employ an independent controller and/or power supply. They may be mounted on the wall or in a corner as well as on the ceiling. They were the first types of motion detector to be used in lighting applications and still remain the most popular type of sensor in use [11]. Installation of these units requires opening the ceiling or wall, since they must be hardwired into the electrical distribution system. This results in a relatively high installation cost for retrofit applications.
- **Wall box-mounted sensors** are primarily designed for retrofit of common wall switches in smaller offices [11]. These units have all components in a single housing and can therefore easily be wired into existing switch boxes in the room. Anyway, there is little design flexibility since the wall box location is fixed typically 110 cm above the floor. Another disadvantage is that room partition and furniture may limit the coverage. In small offices and open conference rooms with wall switches, wall box-mounted sensors are very cost effective as the devices are fairly cheap and the installation cost is almost negligible.

A “false negative” event occurs when the sensor turns the light off while the room is occupied. They are the primary reason why some occupants are not satisfied with occupancy sensors. False negative events can be prevented by use of dual technology occupancy sensors and/or proper setting of the sensors.

False positive events (i. e. lights on when the room is unoccupied) can be prevented by use of manual-on/manual-off/auto-off sensors.

Energy savings for any particular occupant sensor application will vary considerably depending on the size of the area covered and the occupancy pattern but the savings are typically 35 – 45 % [11].

4.7 Daylight Linked Control

Within a daylight-linked control system, photoelectric sensors measure the amount of daylight present and adjust the amount of artificial light accordingly. The photoelectric sensors can either be placed centrally to control several luminaires, or mounted on each luminaire for individual control. Individual control of each luminaire is more expensive to install but provides precise regulation of the lighting level for each part of the area.

Daylight linked control systems operate in two forms:

1 **Photoelectric on/off switching** where it is important to incorporate time delays into the control system to avoid repeated rapid switching e. g. caused by fast moving clouds.

2 **Photoelectric dimming** that ensures the sum of daylight and electric lighting always reaches the designed lighting level by sensing the total light in the controlled area and adjusting the electric lighting.

Photoelectric dimming provides larger energy saving than photoelectric on/off switching and the mode of control is more likely to satisfy the occupants [29].

Automatic daylight linked switching or dimming in day lit spaces is beneficial in rooms with full occupation all the day e. g. in receptions and circulation areas.

4.8 Compatibility with Controls

For existing filament lamp luminaires retrofitted with LED lamps and fed through a 2-wire dimmer in the installation, lack of compatibility presents a potential barrier to the uptake of efficient LED lighting. It relates to compatibility with both leading and trailing edge dimmers in existing lighting systems already installed.

In procurement of this kind of retrofit it is recommended to use LED lighting that is compatible with the existing dimmers.

In the procurement of new LED control system, it is recommended to be interoperable with a wide range of LED products, to ensure the user is not stranded with a system that cannot be used if LED products other than those supplied with the control system are used.

4.9 Smart lighting

Smart lamps and luminaires combine technology breakthroughs in wireless communications and LEDs. Some of the smart features are:

- Colour tuning, dimming, on/off and gradually changing/adjusting the lighting over time
- Connectivity for activation of services, security monitoring and data delivery
- Monitoring of energy consumption or customer visits/movements plus data storage
- Signal boosting/extension
- Built-in presence detector that is linked with the building automation system to control the lighting and the ventilation
- Built-in thermocouples that are linked to the building automation system to control the HVAC system (no impact on lighting)
- Maintain constant luminous flux and operation that ensure the rated lifetime holds

Wireless features imply that smart lamps and luminaires consume energy whenever the mains power is switched on, even when they are not providing lighting but waiting for an instruction from a control device. Many systems also require a separate energy-consuming gateway device for translating the communication signal between the control device and the lamps/luminaires.

It is very important to request information concerning:

1. **Standby consumption** for the wireless control as well as for wired control. The first indicative measurements for wireless controlled domestic products [10] did show very large variation in the standby power for different products and this might very well also be the case for smart lighting products and systems for the tertiary sector.

2. **Information regarding the power supply of all driver components in the standby mode.** In that event that the whole driver is always switched on, this has a great influence on the lifetime, e. g. with a 30000 h lifetime, the driver would have to be replaced before 3.5 years.

3. For commercial buildings, many of the present systems rely on proprietary hardware and software and different protocols are typically used in the building automation systems. It is therefore important to acknowledge that if an **open protocol is** used in the communication of the smart lighting system (including smart lamps, gateways, luminaires, controls, meters and management systems) and if the system is **interoperable with other products/systems**. Lack of interoperability between different manufacturers' smart lighting products is an issue and poses a great challenge.

Efforts to bring more standardisation and interoperability to the market are underway. Manufacturer alliances are formed for several protocols but with each only dealing with use of their own protocol.

The market potential of smart lighting is extensive, once the platform enabling functionality has been established. Smart lighting products can be used in museums, exhibition halls, shopping centres and supermarkets, where the lamps might be used as WiFi or LiFi nodes to help consumers with smart phones to navigate a building or find products in a store [20, 19]. In these premises, the daily hours of operation are typically high and the overall efficacy is thus relatively high, but control features can be used to realise energy savings by turning off lights which would normally remain on. The smart lights and smart phones interaction could activate visual and aural information for self-guided museum tours or product information in a store.

4.10 Human Centric Lighting

Until around 200 years ago, 90 % of our waking time was spent outside. People have evolved in harmony with the earth's most common natural lighting cycle:

- Low light levels and low CCTs (Correlated Colour Temperature) in the early morning
- High light levels and high CCTs at midday (up to 10,000 K)
- Low light levels and low CCTs during the evening
- Extremely low light levels and a medium CCT under moonlight.

Figure 11 *Sunlight variation during a Summer day above the polar circle*

These varying light levels are at the heart of a human being's 24-hour internal clock, otherwise defined as circadian rhythm. Today a large part of the population spend around 90 % of the time indoors with electric lighting. When at work, our lighting is usually set at a consistent level with a constant CCT. This is not consistent with circadian rhythm which can be disrupted without regular and direct exposure to dynamic lighting. This can lead to health issues as light and darkness control the production of specific hormones.

With a natural circadian rhythm, the following hormones are produced during the day [12]:

- Dopamine for pleasure, alertness and muscle coordination;
- Seratonin , a natural mood stabiliser which also helps digestion
- Cortisol for stress response
- Melatonin for sleep

Recent discovery of intrinsically photosensitive retinal ganglion cells (ipRGC) in our bodies show these are very important in setting the internal clock. Light that is rich in blue content stimulates the ipRGC photoreceptors, makes the pupils smaller, encourages dopamine, serotonin, and cortisol production but suppresses melatonin. Long term exposure to light rich in blue content during the day can lead people to be more alert and productive at work. Evening and shift work can results in raised blue light exposure from DSE, lead to too little melatonin and sleep problems.

LED lighting with control is capable of providing variation in luminance and correlated colour temperature e. g. 1800 to 6500 K. LED lighting thus can provide the natural lighting cycle for people. This is called Human Centric Lighting (HCL).

Several hospitals have installed HCL and reported that the patients recovered faster with HCL and the staff felt more comfortable. In future, HCL might also be introduced in offices and other room types.

5. Procurement Criteria

This chapter is the core of the guidelines as explained in part 1.3 and illustrated by figure 1. Procurement staff and decision makers might start by reading this chapter about procurement criteria. Additionally, the reader can search for background information in the supporting Lighting Design (lighting quality), Energy efficiency & LCC and Lighting Control chapters. The subsequent and last chapter provides Best Practice information for each of the main customer categories within the service sector: offices, schools, museums and exhibitions, retail and healthcare.

The goal of the criteria is to support procurement projects including both installation of lighting in new buildings and retrofit of the lighting in existing buildings. The type of criteria included both requirements at lighting system level and component level.

In the ongoing transition to use of LED lighting technology, it is important to focus on both the large opportunities for energy efficiency as well as high quality lighting. The LED technology is very different from former lighting technologies and holds many of possibilities for innovation e. g. through optimised luminaires, built-in lighting, flexible lighting control, colour temperature, imitation of outdoor lighting variation throughout the day, smart lighting and better use of daylight.

The main parameters are included in the procurement criteria while innovation is addressed in the lighting design specification and analysis. The criteria includes parameters such as energy and power consumption, efficacy for light sources, standby, colour temperature, colour rendering, lifetime, compatibility, flicker, lighting control, life cycle cost and maintenance.

The main business models in the tertiary sector are ESCO, self-made and framework contracts [32, 33 and 34]. Depending on the national framework, projects may be carried with a mix of different financial options: own funding, third party financing, leasing, ESCO financing, rebates, incentives and others. More information about this topic can be found at www.premiumlightpro.eu/indoor-lighting/funding-concepts.

5.1 Power and Energy Consumption for new Lighting Systems

In 2012, the EU defined Green Public Procurement (GPP) criteria for indoor lighting as a voluntary instrument [6]. However, at the time of writing, these criteria are out of date due to technological LED development.

In Switzerland, a new standard [3] is about to be published detailing maximum W/m² for design of new installations including lamps, ballast/drivers and control gear (still in accordance with illuminance levels in EN 12464-1:2011).

The Swiss standard operates with a maximum W/m² value and a lower target value. After further evaluation, it was decided to calculate the average of these two sets of values and use these as recommendations with the same customer categories division as in the Swiss standard [3]. This average between the so called target and threshold levels is also recommended by the Minergie program [3].

The **Premium Light Pro recommendation** is to use the requirements shown in table 2.

Table 2 *Maximum power consumption in W/m² for new lighting systems*

Type of building and room		Maximum W/m²
Art	Theater room	5.8
	Hall	5.8
	Exhibition hall	5.8
Hospital	Patient room	5.6
	Observation room	10.3
	Treatment room	10.3
Hotel	Guest room	6.4
	Lobby	5.5
Office	Single and Group room	10,3
	Large room	8,1
	Meeting room	10.3
	Hall	5.9
Restaurant	Restaurant	4.9
	Cafeteria	2.9
	Kitchen in restaurant	15.5
	Kitchen in Cafeteria	12.1
Retail	Food sales	12.3
	Shop	12.3
	Furniture sales	9.9
School	Class room	9.1
	Teachers room	6.2
	Library	4.9
	Concert hall	8.1
	Laboratories	9.1
Sport	Gym	9.3
	Fitness room	5.3
	Swimming hall	6.0
Parking area, Park house and others	Traffic area	2.9
	Hospital traffic area	5.9
	Stairwell	5.9
	Outbuildings	2.5
	Kitchen, Tea room	4.2
	WC, Bath, Shower	5.0
	WC	8.2
	Wardrobe, shower	4.7
	Car park	1.2
	Wash and Dry room	7.0
	Cooling room	2.3
	Server room	2.8

5.2 Light Sources

In November 2016, IEA 4E SSL [1] published updated efficacy requirements for light sources. In this reference, tier 2 covers the top 20–30% of the market products in 2015. Following these requirements with simplification to 5 types of light sources, the **Premium Light Pro recommendation** is to require:

- ≥ 90 lm/W for non-directional LED lamps that emit ≥ 100 lm.
- ≥ 85 lm/W for directional LED lamps that emit ≥ 100 lm.
- ≥120 lm/W for linear LED lamps nominal length of 550 mm to 1500 mm.
- ≥90 lm/W for small integrated LED luminaires with remote control gear where the luminous flux ≥ 100 lm and < 2,500 lm.
- ≥105 lm/W for large integrated LED luminaires with remote control gear where the luminous ≥ 2,500 lm and < 50,000 lm.

5.3 Standby Power Consumption

Technology breakthroughs in wireless communications and LEDs has opened up for a fast growing market for smart lamps and luminaires with multiple features. These include colour tuning, dimming, connectivity for activation of services, security monitoring and data delivery, monitoring of energy consumption or customer visits/movements plus data storage, signal boosting/extension,and built in presence detection. Linking with the building automation system enables users to control the lighting and ventilation.

Using wireless communication generally means that smart lamps and luminaires consume energy whenever mains power is switched on, even when they are not providing lighting but waiting for an instruction from a control device.

For lighting products and systems with standby modes the **Premium Light Pro recommendation** is to require:

- Information about the size of all kinds of standby power consumption (W)
- Information about if there is power supply for all driver components in standby mode and how this influences the driver lifetime.
- Information about interoperability (use of open communication protocol)

5.4 Lighting Control

Operating hours for lighting in the service sector are often long with lights on constantly throughout the day. Implementation of different types of lighting control can lead to large energy savings.

The procurer has to specify the types of lighting control, lighting levels and other features. Thus no general criteria can be specified.

In case the procurement includes lighting control, **Premium Light Pro's recommendation**s are:

- The contracting authority should inform the installer regarding how the space is occupied and used, as well as all particular lighting control requirements including safety and security issues
- To include contract performance clauses requiring that all lighting controls work properly
- Provision of occupant guidelines ensuring that occupants can properly use the lighting control systems.
- Information for the maintenance staff to be used for adjustment of the lighting in case the use of the room changes.

5.5 Colour Temperature, Tolerance and maintenance

LED lighting systems can be provided with different Correlated Colour Temperatures (CCT). It is therefore important to select the CCT that is most suitable for each type of room and task.

The **Premium Light Pro recommendation** is to select one of the nominal CCTs in table 3 consistent with the specified chromaticity quadrangles and Duv tolerances (as per ANSI C78.377: 2015 Specifications for the Chromaticity of Solid State Lighting Products) [1, Tier 3]:

Table 3 *Nominal CCTs and quadrangles and Duv tolerances*

Nominal CCT (K)	Centre Point of Circle		Radius of Circle
	CCT (K)	Duv	
2200	2238	0.0000	0.0044 in (u', v') diagram
2500	2460	0.0000	
2700	2725	0.0000	
3000	3045	0.0001	
3500	3465	0.0005	
4000	3985	0.0010	
4500	4503	0.0015	
5000	5029	0.0020	
5700	5667	0.0025	
6500	6532	0.0031	

The recommendation [1] concerning **colour maintenance** is to require a maximum shift in chromaticity co-ordinates after 6000 hours of operation:

- Δ u',v' (6000 hours) $\leq$ 0.004.

Compared to the MacAdam steps method, the ANSI requirements above are recommended as the requirements are specified for all nominel CCTs and the center points are specified.

If specifying by MacAdam steps is preferred, the recommendations are:

LED colour tolerance requirements:
<= 5 SDCM as minimum criterion in general
<= 3 SDCM for work with visual task.

LED colour maintenance requirements for 6000h:
<= 7 SDCM as minimum criterion in general
<= 5 SDCM for work with visual task.

5.6 Colour Rendering

Colour rendering defines the ability of a white light source to render object colours accurately. The standard EN12464-1 specifies minimum colour rendering requirements for a wide range of tasks by CRI (Ra). In general, a CRI above 80 is considered sufficient for accurate colour judgement in most indoor spaces. However, it is found [1] that for LED light sources the measurement of red colours generally has to achieve a positive value to allow for a good rendering of red colours **$R_9 > 0$**.

The **Premium Light Pro recommendation** is to require:

- **CRI $\geq$ 80 plus $R_9 > 0$** as minimum criterion in general

- **CRI $\geq$ 90 plus $R_9 > 0$** for work with visual tasks of high priority e.g. clinical areas in hospitals, other types of health care, museums, theatres, work with colour inspection/control/selection and some types of shops e.g. clothing selling.

5.7 Rated Lifetime

High-quality LEDs can maintain the light output for tens of thousands of hours. The built-in electronic driver, however, may show a sudden failure. Therefore, it is important to consider the lifetime of the entire lighting system.

The **Premium Light Pro requirements** concerning minimum rated lifetimes are ($L_{80}B_{50}$ which is a little higher than tier 2 in [1]) and lumen maintenance at 6000 h [1]:

Table 4 *Minimum rated lifetimes and lumen maintenance at 6000 h*

Lamp/luminaire	Minimum rated lifetime $L_{80}B_{50}$	Lumen maintenance, 6000 h
Non-directional and directional LED lamps	20,000	≥ 93,5 % of initial flux
Linear LED tubes	35,000	≥ 96.2 % of initial flux
Small integrated LED luminaires (< 2500 lm)	40,000	≥ 96,7 % of initial flux
Large integrated LED luminaires (2500 – 50,000 lm)	50,000	≥ 97.4 % of initial flux

The recommendation [1] concerning early failure rate is to require maximum 5 % early failures at 6000 hours.

It is also recommended to require documentation by test reports from the manufacturers (including extrapolation to reach the rated lifetime).

5.8 Ambient Temperature and Driver Type

LED Luminaire performance is influenced by the ambient temperature. The rated ambient temperature (ta) is the highest sustained temperature at which the luminaire may be operated under normal operating conditions.

Depending on the application, **Premium Light Pro recommendation** is to consider to procure for an **ambient temperature ta = 30 °C** as this could be the ambient temperature in summer with still air around the ceiling.

Concerning the longevity of the LED lighting system it is recommended to require inclusion of controls that ensure the operating temperature stays below the t_q limit.

If the driver is replaceable, it is for maintenance recommended to require information about if the driver type is SELV (Safety Extra Low Voltage) or NON-SELV.

5.9 Power Factor and Harmonic Distortion

For the electrical power supplier, power factor is of high importance. Large customers in the service sector may be subject to a penalty charge from utilities if the power factor is below 0.9. The importance of high power factor may vary depending on the mix of loads in the power distribution network.

Premium Light Pro recommends to require [1]:

Non-directional and directional lamps:
< 25 W: PF > 0.50
≥ 25 W: PF > 0.90

Linear LED tubes (self-ballasted lamps): PF > 0.90

Small and large integrated LED luminaires: PF > 0.90

For harmonic distortion, for products with power > 25 W it is recommended to use the requirements for class C equipment in standard IEC 61000-3-2 [1] which are shown in table 5.

Table 5 *Harmonic distortion requirement*

Harmonic order (n)	Maximum possible harmonic current expressed as a percentage of the input current at the fundamental frequency (%)
2	2
3	30 – CPF (CPF is the ciruit power factor)
5	10
7	7
9	5
11 ≤ n ≤ 39 (odd harmonics only)	3

5.10 Flicker

Power supplies using pulse-width modulation makes the LED blink/flicker with a certain frequency (typically between 100 and 150 Hz). The flicker frequency is not directly visible but may cause visual disturbance as:

- Stroboscopic effects on rotating objects (making it look like it is not moving or as if it rotates at another speed or direction)

- "Cascades" of bright points in the visual field when moving the visual direction rapidly i.e. when turning the head

IEEE 1789:2015 includes flicker requirements with priority on restricting the visible modulation of light (including flicker) at frequencies ≤ 90 Hz, as more research is required beyond 90 Hz (i.e. non-visible effects). Currently, there is no standard for the photometric measurement of modulated light available.

Based on IEA 4E SSL [1] and IEEE 1789:2015 **Premium Light Pro recommendation** is to require:

f: Flicker frequency (Hz)	FM: Flicker modulation maximum (%)
f ≤ 90Hz	FM ≤ (0.025 × f)
90Hz ≤ f ≤ 1250Hz	FM ≤ (0.08 × f)
f > 1250Hz	No FM requirement

Concerning dimming, it is recommended to require that no flicker appears for all important dimming levels (e.g. 50% and 25%) [41].

5.11 Glare and Photo-biological Safety

Glare appears in case of very high luminance or large luminance contrast often due to lack of shielding for a window, reflection or direct sight to the LED light sources in the luminaire.

Premium Light Pro recommendation is to require:

1 Avoidance of direct glare [standard EN12464-1]:
- Specification of the minimum shielding angle in all directions depending on the lamp luminance
- Specification of the discomfort glare by the UGR_L

2 Avoidance of high angle luminance glare [1, 42]:
- When the gamma (γ) angle exceeds 60 degrees, the light source luminance shall be no more than 10,000 cd/m^2.

3 Photo-biological safety that ensures the human eye is not harmed by intensive bluelight radiation (blue light hazard) [1]:
- LED lamps and luminaires with RG0 or RG1 [see standard IEC 62471/CIE S009]

5.12 Dimmer Compatibility and Operation

Dimmer compatibility is of high importance as many LED products are often not completely compatible with currently installed dimmers. As manufacturers are still trying to define and adopt a new dimming standard, the dimmer compatibility of LED products is likely to continue to be a problem.

Recommended **dimmer compatibility** requirements:
- The manufacturers shall provide an address for a webpage that lists compatible dimmers
- For each compatible dimmer, the manufacturer shall list the range of luminous flux levels a given dimmer-luminaire combination can achieve.

Recommended **dimmer operation** requirements:
- Smooth dimming down to 30% of total luminous flux with no observable flicker and no audible noise.
- When dimmer is set to 100%, the light output shall be ≥ 90% of luminous flux without dimmer.

5.13 Maintenance

Premium Light Pro recommends information to be provided on:
- Lamp Lumen maintenance Factor (LLMF)
- Luminaire maintenance Factor (LMF)
- Maintenance Factor (MF)
- Maintenance plan shall be provided including specified intervals for maintenance and cleaning.

It is also recommended to consider:
- Luminaires with constant luminous flux control for some applications
- Closed LED luminaires for some applications that may encounter significant dirt.

5.14 Life Cycle Cost

The purchasing costs for the LED lighting system are typically higher compared to traditional lighting systems, while the operation and maintenance costs are lower. A life cycle cost calculation can justify the initial investment costs when considering the costs and savings over the lifetime of the lighting system.

Premium Light Pro recommends:
- The lighting system solutions/alternatives should be compared by LCC calculations by the LCC method specified by the procurer.

5.15 Contractor Experience and Obligations

For both the design and the installation team, the tender shall demonstrate that the personnel have experience from at least 5 relevant projects and suitable professional qualifications in electrical or building services engineering. Experience from 15 relevant projects is beneficial.

The contractor shall **ensure the following**:

Installation
- The lighting system is installed exactly as specified/required.
- Delivery of a schedule for the lighting system installation with appended manufacturers' invoices or delivery notes.
- Provision of information so that occupants know how to control the lighting and maintenance staff can make adjustments if necessary (e. g. when room layouts change).

Functionality
- The installed new or renovated lighting systems are working properly and using no more energy than specified.
- Daylight linked controls shall be calibrated to ensure that they switch off the lighting when daylight is adequate.
- Occupancy sensors shall be verified to detect moving objects in application.
- Time switch control (physical and/or software) shall be set to appropriate switch off.
- If after the commissioning, parts of the lighting systems do not appear to meet all specifications and requirements, the contractor shall adjust/recalibrate the systems.

Training
- The contract shall preferably include training of the users with focus on operation, lighting control and maintenance.

Evaluation of the performance
- The contract shall preferably include installation of a metering and measurement system for identification of failures and monitoring that energy consumption is as specified.

Product availability
- It is recommended to require that manufacturers of all procured LED products guarantee product availability over a designated time period.

Substances of Concern
- It is recommended that manufacturers do not use substances of concern in their products. The European Chemical Agency works together with the EC and the EU member States on the safety of human health and the environment by identifying the needs for regulatory risk management at an EU-wide level [39] including the REACH regulation. In connection to this, the Danish Environmental Protection Agency (EPA) [40] has made a "List Of Undesirable Substances" (LOUS) that include 40 substances. The LOUS list is aimed at Danish businesses and serves as a signal and guideline regarding substances that businesses should use less of in the long term or completely phase out. Some of the Danish municipalities require in their procurement that no substances at the LOUS list are included in the procured products.

Waste management
- During the installation of new or renovated lighting systems, waste is to be reduced and all parts are to be separated and recovered in accordance with the WEEE Directive. Some Danish municipalities consider requiring all plastic and metal parts in the products to be suitably labelled so they can be recycled.

5.16 Prequalification Stage

When assessing responses from tenderers for lighting installation contracts, incorporating a pre-qualification stage may be beneficial to screen applicants.

Prequalification of companies might include:

- Presentation of delivery of similar lighting systems in similar projects (of the same size and type) and the time of delivery etc.
- Measurements by a neutral laboratory to document the energy savings
- Presentation concerning how they will be able to integrate their luminaires in the actual buildings
- Presentation of their capability concerning maintenance of the lighting system.

5.17 Evaluation of Tenders

Minimum criteria and requirements specified in the previous sections of this chapter should be fulfilled by any tender. However when awarding contracts, higher quality and efficiency beyond the minimum can be awarded and evaluated by a scoring scheme. Naturally, selection of award criteria and the weighting applied depends on the type of project, type of building(s) and room types. In table 6 are examples of how contractor selection may be made using award criteria, and evaluation of tenders by use of a scoring scheme.

Table 6 *Example of selection of award criteria*

Criterion	Minimum criteria	Award criteria
Cost		
Investment costs	✓	
Life Cycle Costs	✓	✓
Energy Efficiency		
Power and energy consumption	✓	✓
Efficacy for light sources	✓	
Standby power	✓	
Lighting controls	✓	✓
Lighting Quality and Design		
Illuminance level	✓	
Use of daylight, lighting distribution, uniformity, contrast	✓	
Colour temperature, tolerance and maintenance	✓	
Colour rendering	✓	✓
Lifetime	✓	✓
Ambient temperature and driver type	✓	
Power factor and harmonic distortion	✓	
Flicker	✓	
Glare and photo-biological safety	✓	
Dimmer and transformer compatibility	✓	
Maintenance, Installation, Operation, Repair, Recycling		
Maintenance	✓	
Contractor experience and obligation	✓	
Contractor training	✓	✓
Warranty and spare part availability	✓	✓

Table 7 *Example of evaluation of tenders by use of award criteria and weighting*

Award criterion	Weighting [%]
Cost	
Life Cycle Cost	30
Energy Efficiency	
Power and energy consumption	20
Lighting control (depending on the amount extra control features included)	5
Lighting Quality and Design	
Colour rendering	10
Lifetime	15
Installation, Operation, Maintenance, Repair, Recycling	
Contractor training (included or not included)	10
Warranty and spare part availability	10
Total	**100**

6. Best Practice

This chapter provides best practice advice about lighting design, possibilities for improved quality of lighting and increased energy efficiency by use of LED lighting systems.

The chapter includes sections about offices, schools, museums and exhibition, retail and healthcare. Each section – with subsections about room types – is written as an independent document that can be used directly as a checklist at the start of a project of a similar type.

The best practice checklists are to a large extent based on the huge experience of DCL [7] on how to complement efficient LED lighting with the right lighting design.

A general approach for best practice with high quality of lighting and energy efficiency is:

1 Lighting shall be considered from the start of design of a new building or renovation.

2 Use personnel both for design and installation who have experience from similar projects and suitable professional qualifications.

3 Differentiate on the major types of rooms, activities, operation hours, primary staff age group and visual work tasks.

4 When renovating, what kind of lighting is used presently (lamp type, wattage, luminaire type, direct/indirect etc.), and what is the yearly consumption for the applications?

5 When renovating, what is the staff and customers' opinion concerning the present lighting? Do they desire changes or improvements in positioning, the type of lamps and luminaires, ability to control, illuminance or glare levels. The right lighting contributes to creating the right atmosphere appropriate to the activity.

6 Refer to the PremiumLight Pro procurement criteria and assign appropriate award criteria and weighting

7 Investigate use of suitable controls (manual and automatic). LEDs work extremely well with controls, and the savings related to use of timers, daylight or occupancy sensors are generally underestimated. Consider use of more smart or intelligent solutions e. g. human centric lighting with colour tuning, task specific lighting scenarios and connectivity data delivery functions e. g. using LiFi.

8 Perform economical calculations and evaluation.

9 Ensure the selected lighting solutions meet the client's requirements, are well-functioning and easy to use and that it is possible to maintain and adjust them also in the long run.

In general, recommended values for illuminance levels, uniformity, glare and colour rendering can be found in European standard EN12464-1:2011, Light and lighting – Lighting of workplaces – Part 1: Indoor work places. Therefore these values are not stated in every section. Part 2.5 provides information about this important standard.

The chapter includes best practice cases collected in the Premium Light Pro project. More information about the cases including contact can be found at: **www.premiumlightpro.eu**.

6.1 Office Buildings

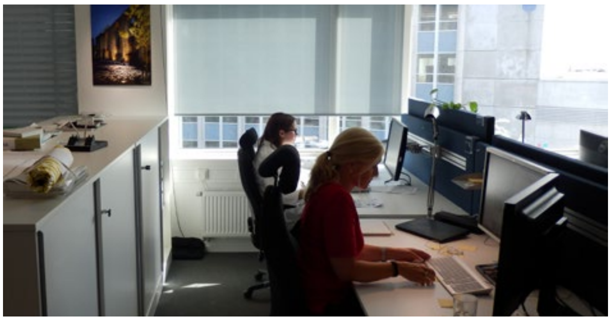
Good lighting in offices enables the occupants to perform their work efficiently without strain or fatigue.

Common for all room types

- A dim lighting level on the floors can be compensated by a perception of brightness by illuminating the walls e. g. by wall-washers – this will define the whole space and helps with alertness.
- With daylight access, automatic lighting control may provide large savings. Sun blinds or curtains shall only be used when it is necessary.
- In case downlighters are used as ceiling lighting, then luminaires with low glare should be used.

Reception

- The reception area forms the first impression for visitors, and must support the organisation's image architecturally and appear bright and welcoming.
- Combine general and localised lighting with dedicated luminaires at work stations and lower (but sufficient) broad light distribution across the entire area..
- Built-in LED lighting can be used under reception desks.
- Pendant lighting used over the counter and alongside visitors' chairs creates small pools of light that contribute to the ambience..
- It is very important that the reception staff can see arriving guests in the entrance very clearly and not as silhouettes against bright daylight or artificial light. It is also important that guests can easily see the reception staff.
- A dim lighting level on floors may be compensated by a perception of brightness by illuminating the walls e. g. by wall-washers – this will define the whole space.
- Entrances are light transitions zones – hence a gradual change of the lighting starting outside the building (from daylight or later total darkness) may be necessary. LED lighting systems can provide this with automatic controls.



Picture: Casper Kofod

Offices

- Make a furnishing plan and select the optimal lighting solution depending on the size of the room, the number of work places, the type of work and the amount of daylight.
- Especially for very large offices, it may be desirable to create small "recreation islands" with cosy lighting for inspiration, relaxation and small discussions.
- The task area may be illuminated by general lighting or dedicated luminaires. A higher work plane illumination is recommended for two main reasons: The occupant's eyes and attention are automatically drawn to areas with more light, and reducing light in the surrounding areas decreases energy consumption effectively compared to higher task lighting from ceiling mounted luminaires.
- Task lighting should come from the opposite side to the occupant's dominant hand.
- Intensive DSE work should be carried out 2–3 meters from the windows.
- For DSE work asymmetric lighting from the work lamps is a benefit.
- Work tables and DSEs should, where possible be placed with screen surfaces perpendicular to the windows to avoid mirroring of windows in screens and high contrast to the outside view.
- In deep office spaces, zonal control and daylight sensor automation can be used to switch off rows of general lighting near the windows.
- For the general lighting, it is often a benefit to install presence sensor controls, especially in spaces that are not used constantly.
- For general lighting, manual onset (as well as automatic off-set) on a dimmed level is an effective energy saving option. Manual on-set forces occupants to choose a proper lighting level and this provides a sense of personal control.

- Simple and intuitive individual adjustable control (on/off, dimming, changing position) is a great benefit, e.g. providing a higher luminous flux for older persons.

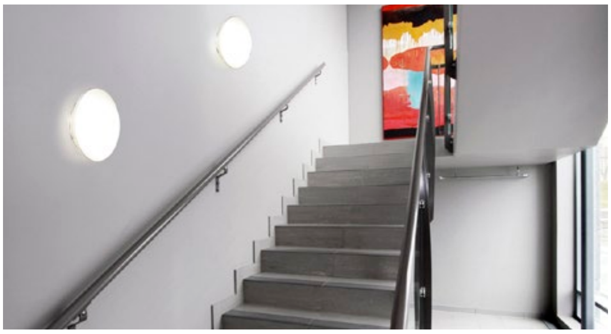
Picture: http://www.osram.com.au/osram_au/applications/office-buildings/conference-room/index.jsp

Conference and meeting rooms

- The general lighting should be controlled by dimmers to facilitate use of different brightness during audio-visual presentations, round table discussion and breaks.
- Use of non-transparent curtains or near total darkness during presentations is not beneficial as the audience may become tired and inattentive.
- For larger rooms, built-in LED table lighting might be used to create small non-disruptive spots of light during presentations useful for reading and taking notes.
- A low illumination at the wall behind the screen/DSE creates a more even luminance pattern in the field of view of observers allowing for greater focus.
- Avoid luminaires facing podiums or display boards that may cause the presenter to experience glare.

Canteen

- Use adjustable ceiling lighting that can provide different lighting levels for coffee and lunch breaks, internal meetings, education, recreation and cleaning.
- It is a benefit if the pendants can be raised or removed for doing other activities.
- Use of low horizontal illuminance along with vertical illumination (walls, furniture and doors) plus table or pendant lights make the canteen pleasant and cosy. Art on the walls should be illuminated by dedicated spots.
- In buffet areas, a direct and high illuminance is recommended to assist recognition of food and speed of service. High colour rendering ensures appreciation of colours in the food.



Picture: http://glamox.com/uk/solutions/stairwells

Corridors and Stairs

- Use bright doorsteps and steps along with a contrasting colour. Further, a mix of diffuse lighting and downward directed light create good perception of space, face recognition and form shaping characteristics (e.g. seeing the steps well) for increased safety.
- Lighting uniformity has to be sufficient for safe movement with no dark areas.
- Luminaires that partly radiate light against a bright ceiling and/or bright walls normally creates a pleasant atmosphere.
- Outside working hours, presence sensor control (maybe with lighting level steps) can be beneficial.

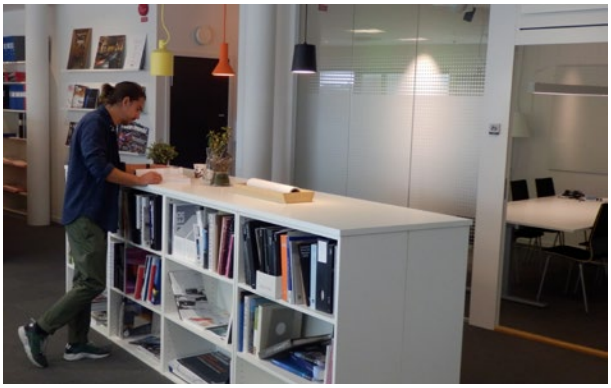
Best Practice example:
New High Quality LED Lighting System

Around 2015, ÅF Lighting conducted a full replacement of the lighting at their 350 m² office in Malmö with LEDs.

Before: LFL and CFL luminaires were used with a constant illuminance of 300 lux. Only one control switch per 20 work stations was present, and no vertical illumination or accent lighting was used.

After: Individual control of all light sources was incorporated. Accent lighting was introduced to illuminate doors.......etc. Pendant luminaires were used to allow for variation in the lighting and accommodate individual needs. Additionally, the ability to control the RGB values of LEDs was introduced, as well as wall art that increased luminosity. Several smaller, localised 'lighting zones' were also created in the L-shaped office. The end result was a greatly improved light distribution, more attractive combinations of colour, and great flexibility for control and application of light to different tasks.

New lighting with spots on the shelves and pendant luminaires

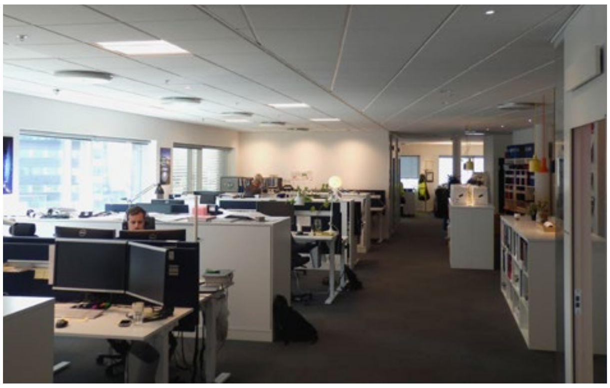


Picture: Casper Kofod

Results: the LOR was nearly doubled, but for around half the power usage of the previous system. 92% energy savings and a 7 year payback time were estimated to have been achieved. Furthermore, positive feedback was received from staff on the improvement of the working environment.

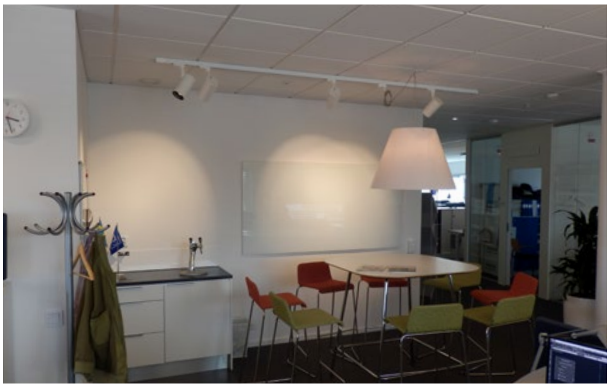
New lighting system

Improved task lighting by accent and vertical lighting



Use of LED RGB lists and vertical lighting

Use of pendant luminaires plus accent and vertical lighting



Added vertical lighting by rosettes

Pictures: Casper Kofod

Best Practice example:
Advanced LED lighting in office building in Katowice

GPP BUSINESS PARK, built in 2014-15 is a complex of three low-energy intelligent office buildings (7200 m^2) in the Silesian Industrial Park in Katowice, which have BREEAM certification. In buildings 2 and 3 an LED lighting system was installed with different types of controls, using certified products with lower environmental impact, contributing to lower CO_2 emission.

A sensor on the building's roof measures the amount of the sunlight and the angle of the solar rays. The control system automatically brightens or dims lighting in the buildings depending on the outside conditions.

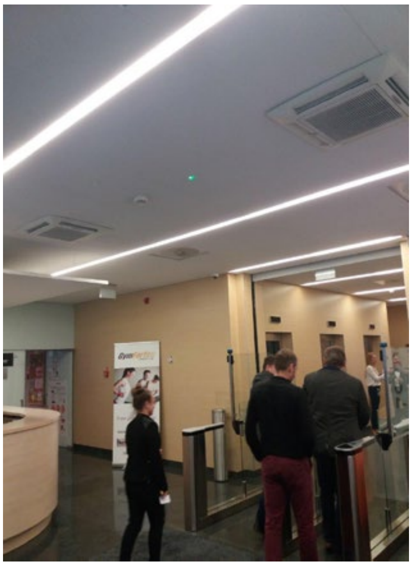
The control system also manages the shutters in order to reduce unpleasant glare from the sun. Sensors are in place that automatically turn the lights off when nobody is present in a room.

The LITENET control system provides an illuminance level of 500 lx at workstations. The implementation of the control system reduces the lighting energy consumption by 40 %, and the average energy consumption is very low around 2 kWh/m^2 per year.

GPP Business PARK in Katowice

New LED tubes and panels

Reference: www.zumtobel.com



6.2 Schools

A strong learning environment relies on good lighting. Our eyesight is so resilient that we are hardly aware of the handicap imposed by poor lighting but this might result in slower reading, little understanding of what we read and diminished concentration.

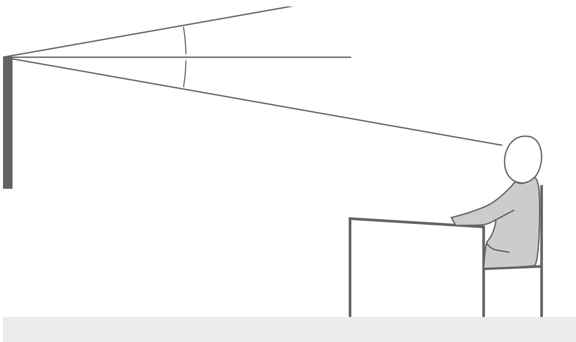
Generally, if regular maintenance, cleaning and replacements of the lighting system are carried out during school holidays then any initially excessive illumination can be reduced with consequent energy savings.

Common for all room types

- A dim lighting level on the floors can be compensated by a perception of brightness by illuminating the walls e.g. by wall-washers – this will define the whole space.
- By enabling daylight harvesting and adjusting levels accordingly, automatic lighting control may provide large savings. Sun blinds or curtains shall only be used when it is necessary.
- Where downlighters are used as ceiling lighting, using lower glare in preferable.

Classrooms

- Traditionally, classrooms have large windows which enhance overall well-being but for use of screen projections, DSEs and smart-boards, effective ways of screening out direct sunlight must be available and easy to operate.
- In larger classrooms, energy saving can be obtained by zonal control of the general lighting. Hence if daylight is sufficient near the windows, nearby rows of general lighting can be switched off, preferably by means of daylight sensor automation.
- Concerning the general lighting, a balance has to be found between the need for a bright space to keep the students alert and the ability to see low-contrast screen projections, which can be difficult to see in a very bright space.
- The general lighting can be optimized for reading, writing and communication by rather providing diffuse lighting with by an appropriate number of luminaires (several smaller luminaires are preferable to fewer larger ones) or by luminaires that project onto bright walls and/or the ceiling.
- Lighting at an inconvenient height, i.e. in the line of sight of the students or directly behind displays should be avoided. Screens and projectors must be placed with screen surfaces perpendicular to window panes and ideally with windows on the left hand side.
- For lighting designed to illuminate display screens and boards, the choice of luminaires and their position as well as the use of matte boards is crucial for the visibility and avoiding glare. Dimming control of the general lighting may also be necessary.
- A conventional whiteboard light should be mounted with some distance to the board to ensure proper illumination of the lower part. However, if mounted too far away with a small horizontal beam, shiny reflections might bother students in the front row (see the illustration below).



- Light that allows for good colour differentiation (useful in subjects such as chemistry, biology or design/technology) can be provided by large windows facing north and luminaires or lamps with a spectrum close to daylight and with a high colour rendering index, e.g. Ra 90.

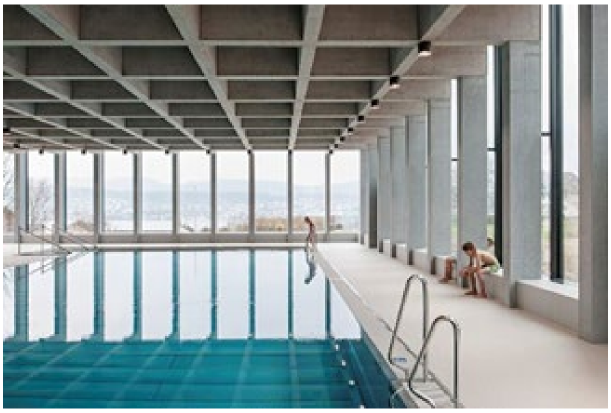
Picture: DCL, Denmark

Corridors and Stairs

- The lighting uniformity has to be sufficient for safe movement without dark areas.
- Appropriate contrast, light from windows and different colours floor darker than walls and ceiling brighter than the walls) can support indoor visibility. The picture above shows an excellent example of this application.
- Lighting of stairs should ensure that treads look bright and risers look dark. This implies lighting from upstairs rather than from downstairs. Further, a mix between diffuse lighting and downward directed light creates good perception of space, facial recognition and form shaping characteristics (seeing steps well).
- Corridors and stairs are mainly used during breaks, and hence presence sensor lighting control may enable energy significant energy savings. It is recommended to dim down to 10–20% of the full luminous flux to avoid the corridor appearing too dark and empty.

Foyer and Assembly Hall

- Appropriate lighting should be provided for any activities that may take place, e.g. presentation, examination and amateur theatre. It may even be appropriate to install two or more independent lighting systems, such as light for presentations, cleaning activities, and accent lighting/stage lighting.
- In a foyer with stairs or a hall with a high ceiling, long-life LED overhead lights may be installed. Alternatively, long-life LED up-light luminaires may be used.
- For stairs in the foyer, the steps should be marked with a contrasting colour, and built-in, dimmable LED step lighting may be installed. For safety reasons, it is important that steps are clearly visible even when light is dimmed far down.
- Dimmed and diffuse illumination without contrast should be avoided as it may affect the concentration of the audience.
- In an assembly hall, or auditorium it can a good idea to place the screen in a niche that shields from direct light and allows for lighting of the podium and the speaker.



Picture: http://www.archello.com/en/project/swimming-pool-de-vrolijkheid/2042222

Gymnasiums and Swimming Pools

- Daylight is very welcome but safety will influence the choice and position of luminaires as they need robust protection from damages in areas where sport is being played.
- Dimming of the general lighting is needed if the gymnasium is also used for examinations, celebrations, music concerts and others.
- In swimming halls, the lighting design shall minimise bright reflections in the water surface. LED luminaires can be made extremely watertight and gastight (chlorine gases) and are ideal for most purposes except sauna.
- Time switch control is recommended for switching off the lighting at fixed times according to the occupancy plan for use of gymnasium or swimming pool.
- More recommendations can be found in the standard EN 12193:2007 Light and lighting: Sports lighting.

Best Practice example:
Warm and cool white lighting supporting more effective learning

Westbrook Lane School in Leeds conducted full retrofit of their old lighting system and replaced with LED light sources.

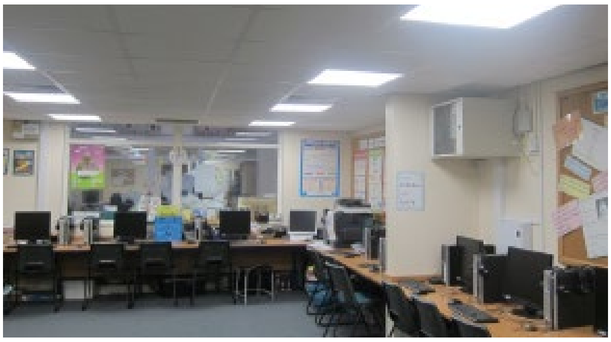
Before: 198 luminaires with LFL T8 or T12, bulkhead and PL lamps plus 7 external HPSA floodlights. The school complained about poor lux levels in class rooms and frequent maintenance and cleaning.

After: 221 LED luminaire with specified different white colour temperatures. No lighting control was installed. The safety was improved with the sufficient lux levels. The retrofit was finalised by the end of 2015.

Result: The retrofit resulted in 59 % energy savings. The payback period is 8 years.

The Energy Saving Trust, UK, has chosen this case as best practice due to improvement of the learning environment by a combination of use of warm and cool white LED lighting.

The new LED lighting

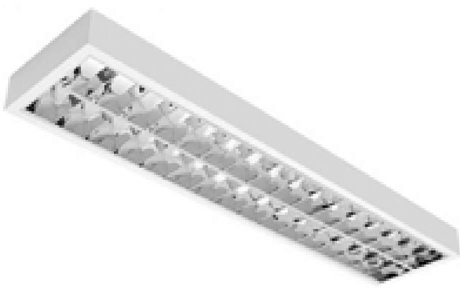


Best Practice example:
LED retrofit of TGM technical school in Vienna

GM Wien Technical School specialises in energy efficiency and sustainability. In 2013, the school decided to retrofit the classrooms with LED lighting in order to obtain a better learning atmosphere for the students and a significantly reduction of the energy and operating costs. LED ceiling lights were chosen to create the feeling of having natural lighting in the classroom.

A lighting control system was installed to measure the intensity of sunlight. This was used to automatically control the lighting by reducing its brightness in accordance with levels of natural light outside. A control panel was installed in every room, making it possible to choose between three different lighting scenes. The retrofit was finalised in 2015. It resulted in 67 % energy savings and the payback period is 6 years.

The old fluorescent lighting T8 luminaire



The LED luminaires

6.3 Museums and Exhibition

LEDs can be combined in any shape to produce highly efficient illumination. Individual LEDs can be dimmed, resulting in a dynamic control of light, colour and distribution. Well-designed LED illumination systems can achieve fantastic lighting effects both for the eye, the mood and the mind. Therefore, LED lighting provides many opportunities for museums and exhibitions.

Art area

- LED illumination produces little infrared light, close to no UV emissions and little radiated heat emission. LED is therefore appropriate for sensitive objects as paintings, art galleries, archeological sites etc. In cases where cooling was used in the former lighting system (eg. alongside halogen lamps), energy savings may be realised due due to this not being necessary with an LED system.
- Choosing the right white LED light source in terms of spectral qualities (colour temperature), colour rendering, luminaires and type (simulating the diffuse daylight or some kind of direct lighting) can have a tremendous impact on perception. Ideally it might be curated along with the specific pieces of art.
- Using LED RGB lamps with colour tunability makes it possible to provide colour.
- Museum LED lighting might be used to create a different perception of the art at night. This is used at the museum Glyptoteket in Copenhagen (see the image below with skylight in the day).

Corridors and Stairs

- Luminaires that partly radiate light against a bright ceiling and/or bright walls often creates a pleasant atmosphere.
- The lighting uniformity has to be sufficient for safe movement with no areas experiencing low visibility.

- Lighting of stairs should ensure that treads look bright and risers look dark. This creates the perception of lighting from upstairs rather than from downstairs. Mixing diffuse lighting and downward directed light can improve perception of space, facial recognition and form shaping characteristics (e. g. steps).
- In case of daylight access, automatic lighting control may provide large savings.

Pictures: Casper Kofod

Assembly Halls

- Daylight and visual contact with the outdoor environment is beneficial for well-being and will reduce energy consumption, but sun shielding control is also necessary.
- Suitable lighting should be provided for different activities: presentations, debates, performances and cleaning. It may even be appropriate to install more than one lighting system.
- If the ceiling is high, long-life LED overhead lights or up-light luminaires may be used.
- For stairs, the steps should be marked with a contrasting colour and could also utilise built-in dimmable LED step lighting. However, the steps must always be clearly visible.
- Dimmed and diffuse illumination without contrast should be avoided as it may affect the concentration of the audience.

Best Practice example:
LED retrofit of the historical town hall in Bremen

The historical town hall in Bremen built in the early 15th century is listed as a World Heritage site. Previously, this was lit by traditional filament lamps.

In 2014, a panel of experts was established to investigate an upgrade to LED lamps. The quality (colour temperature, colour rendering, design and weight) and aesthetic requirements were a very important consideration for the historical illumination.

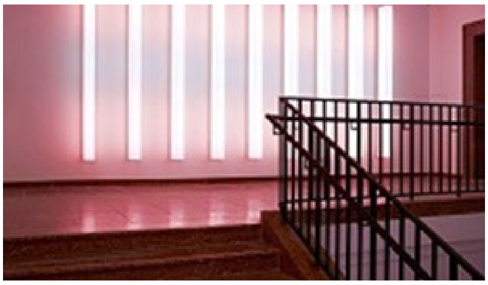
Following careful selection, a suitable LED lighting system was identified and installed in 2016. The payback period was less than 2 years.

The new lighting system

Example of using efficient LED lighting as an artistic medium

The Lenbachhaus museum in Munich explores use of energy efficient LED lights as an artistic medium, e. g. the northern staircase (see below) features sculptural red-white-red lighting.

More than 170,000 LEDs and intelligent lighting control enable almost 100 different colour tones and dimming levels to be set. Curators are thus able to display each work of art in their ideal light. Many other museums are highly interested in this innovative lighting concept.



6.4 Retail

Attracting the attention of customers in a shopping centre with so many other distractions and competing stores can be very difficult, but a well thought-out lighting system can be a successful tool to help achieve this. The right lighting sets the right mood and incites the willingness to buy. Typically, retail chains have to adhere to a very strict corporately recognisable lighting design.

LED lighting provides many possibilities to achieve fantastic lighting effects, not only for the eye but also to create the desired ambience and well-being.

It is important that staff benefit from good visual conditions without glare. Unfortunately, too many shops equate lighting quality with lighting quantity resulting in over-lighting and far from optimal conditions. Shop lighting should be differentiated and guide customers through the shop with points that encourage them to stop and look.

- Many shops have problems with excess heat generated by incandescent or halogen lighting. Upgrading to LED lighting solves this problem and energy consumption may be lower as a result.
- Window display lighting can help attract customers and support the profile and image of the shop. Colour tunable LED lamps make it possible to vary the appearance of items on display. Programmed colour shifts over time can be a part of the display.
- The lighting in the entrance area should be of optimal brightness to attract attention and provide a smooth transition zone between the daylight and the indoor lighting.
- It is recommended to divide the store into zones with different needs for lighting: check-out counter, entrance, exhibition, low podiums, high shelving, traffic, dressing rooms etc.
- Since the eye is attracted to and adjusts its sensitivity to the brightest parts in the field of vision it may be desirable to create peak brightness on the important items for sale, medium light on the "ordinary goods" and less, but sufficient lighting in the traffic area.
- Accent lighting by well-placed spots is another useful design tool which can highlight shapes, colours and texture. This creates life in the shop.
- Very large contrasts in illuminance and luminance shall be avoided as this can be inconvenient and tiring for the staff.
- Built-in LED lighting in glass cabinets and coolers can accentuate and display products.
- In general, it is necessary to avoid glare from light sources as well as mirroring and reflectance from bright surfaces.
- Local functional lighting over sales counters can help create focus, a friendly atmosphere and increase visibility of money, credit cards etc.
- Lighting in backrooms and storage needs to be sufficient for the work and further energy savings can be achieved by installing presence sensors for control of the lighting.

Best Practice example: Better lighting quality, no "overlighting" and huge savings

The bookstore La Capell in Barcelona was retrofitted in 2015 – 2016 with LED lighting.

Before: The system included 1170 CFLs, 10 LFLs and 70 halogen spots, with some lighting integrated into bookshelves. In many cases, the optimal positioning and brightness of lighting for a bookstore were not selected. The overall effect was one of excessive luminance in the store.

After: As a general reduction in brightness was desired, the system was able to upgraded with significantly fewer lamps. 54 LED spots and 18 slim LED luminaires were used, resulting in not only an improved ambience, but also significant energy savings and better presentation of the books. The new luminous flux was measured to be 20% of the previous amount.

Results: Annual energy consumption was reduced to 10% of that of the previous lighting system, and a reduction in the tariff for peak consumption was also seen. The new system required significantly less maintenance and has a payback period of less than a year. In addition, the bookstore saw an increase in sales following the installation.

A key part of the process to initiate the installation was demonstration of the lighting system by the contractor, which was carried out by installing a sample of the lighting for the bookstore management to see the aesthetic benefits. A high quality installation was carried out, reinforcing the benefits of using a suitably experienced and skilled installer.

The old lighting

The new lighting

Best Practice example:
Retrofit of incandescent 'squirrel cage' bulb in café in Leeds

The incandescent 'squirrel cage' bulb has been a popular design trend in recent years in bars, cafes, restaurants and shops. These lamps remained at the market after the incandescent ban in 2012 due to a loophole in EU lighting regulation. These bulbs provide a very warm white light (around 2200 K) with a vintage design.

The loophole was closed in 2016. At this time, quality LED retrofit came at the market. The LED lamps have the same stylish ambience and look, colour temperature and a high colour rendering at 90 Ra.

The LED lamp uses a tenth of the incandescent lamp power and has a rated lifetime of 15,000 hours. The payback period was less than half a year.

Very positive feedback was received on the aesthetics of the new LED lighting from the café's owner, the customers as well as on social media.

The new lighting

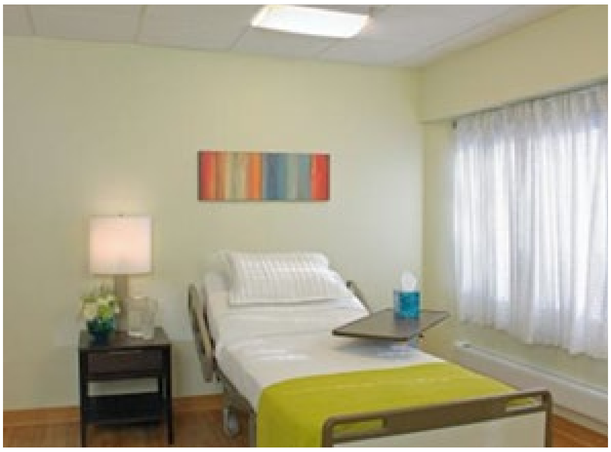
6.5 Healthcare

The quality and quantity of lighting is an important consideration in the speed of recovery and well-being in healthcare. Most healthcare activities are performed indoors with use of electric lighting.

Traditionally, healthcare lighting is set at one level with a constant CCT. This is not consistent with the human circadian rhythms where during the day is regulates levels of dopamine, seratonin, cortisol and melatonin. Without regular and direct exposure to daylight lighting, the circadian rhythm can be disrupted, which can lead to health issues such as sleep problems as light and darkness control hormone production.

Some LED lighting provides capability to dim and "tune" the correlated colour temperature which can improve physical conditions for patients. Carefully designed lighting can support circadian rhythms in patients. The lighting can be provided by LED dimmable fixtures e.g. able to be tuned from 1800 to 6500 K.

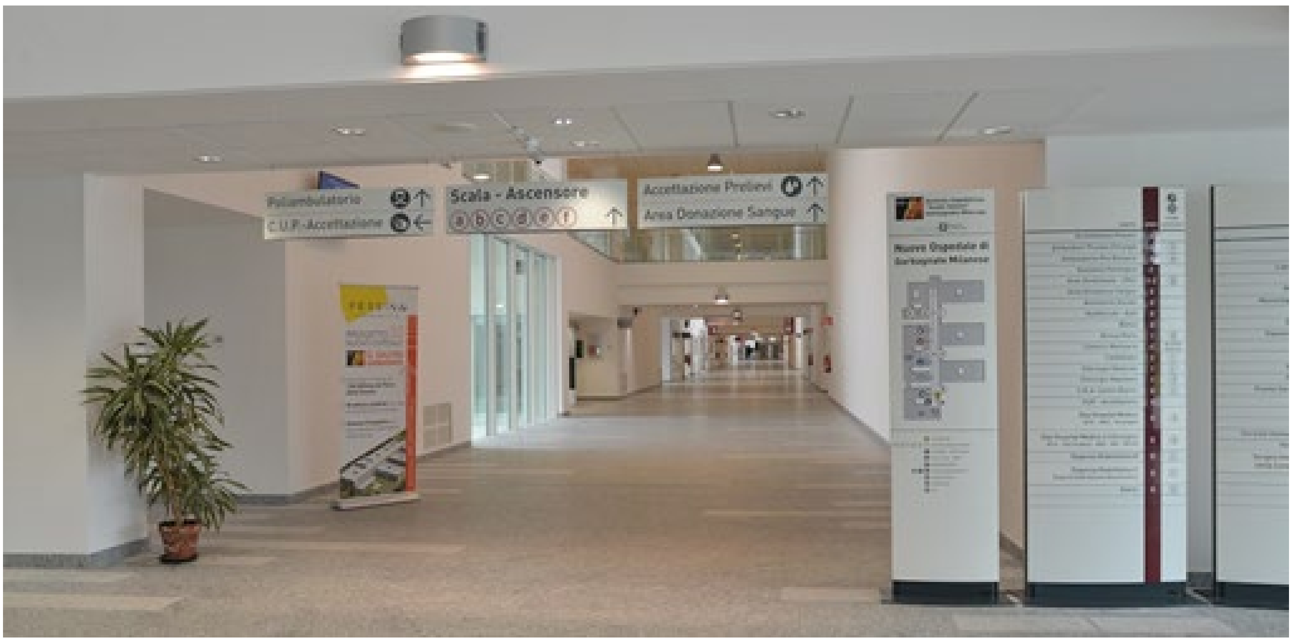
Human centric lighting is being increasingly installed, especially in hospitals where the patients spend almost 100 % of their time indoors, and artificial lighting that mimics the non-visual, physiological effects of daylight has been shown to be beneficial.



Picture: http://www.visalighting.com/unity-patient-room-lighting-now-led

Patient rooms

- Access to nature and daylight helps recovery.
- Adding light to walls and ceiling creates a sensation of brightness even if the illuminance is low.
- Built-in LED table lighting can be useful to aid visibility in tasks and avoid disturbing other patients.
- In the morning, bright light can contribute to the patient's circadian rhythm and overall wellbeing. Dimming control for the general lighting provides flexibility that allows a high illuminance in the morning and during cleaning activities.
- At night-time red night lighting can help prevents disturbance of the patient's circadian rhythm.
- LED lighting can provide human centric lighting that mimics the non-visual, physiological effects of daylight including the facilities mentioned above.
- Individual control e.g. by mobile table light and reading lamps is often desirable.



Corridors and Stairs

- The lighting uniformity must be sufficient for safe movement without dark areas.
- Lighting of stairs should ensure that treads look bright and risers look dark. This implies lighting from upstairs rather than from downstairs. Further, a mix between diffuse lighting and downward directed light creates good perception of space, facial recognition and form shaping characteristics (good visibility of the steps).
- Corridor and stairwell lighting is typically always turned on. Savings can be obtained by dimming night lighting in corridors, and if a reddish or amber colour is used this helps prevent disturbance of the patient's circadian rhythm and sleep patterns.

Operating Theatres

Lighting for operating theatres is highly advanced and should be provided by a specialist supplier. The guidance here is thus limited to mentioning two general advantages by use of LED lighting systems:

- The spectrum of the LED lighting can be adjusted to what is important to see during the operation.
- Many operations are performed as keyhole surgery, meaning that the surgeon needs excellent lighting both when observing the patient and DSEs. At the DSE the surgeon has to be able to distinguish between many variations of red and other colours for extended periods of time. LED lighting systems are beneficial by means of their ability to provide flexibility of light focus and colour rendering.

Best Practice example:
Retrofit with use of glare free LED Human Centric Lighting

In 2016, the Danish Slagelse hospital finalised a retrofit of their lighting system where they were required to maintain certain building features, including the acoustic ceiling and recessed openings of the luminaires.

Before: The previous system consisted of 1640 LFL luminaires. Problems with glare, low illuminance and frequent cleaning were reported.

After: The system was upgraded to closed dust-free LED dimmable luminaires with better lighting spectrum providing Human Centric Lighting by DALI control.

Results: An increase in luminous flux of 28% was produced by the new lighting, with 33% lower energy costs. The installation had a payback time of 5 years.

Optional: The option remained for further upgrade of the system by adding daylight and PIR sensors. This would be estimated to provide further savings of up to 40%.

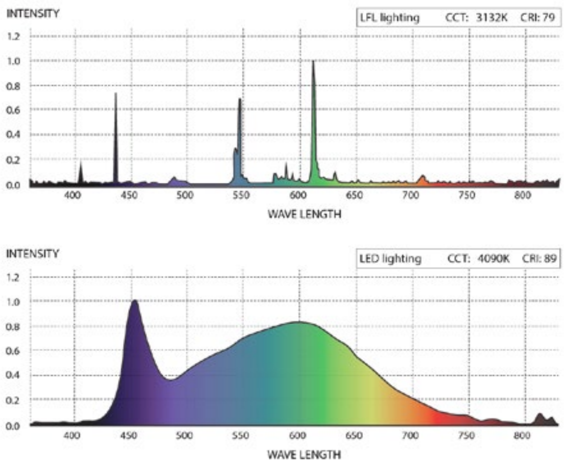
The new LED lighting increased the functionality and quality of light in the hospital at a lower cost, solved issues with glare and maintenance, and improved well-being for patients, visitors and employees. The new LED lighting is considered a best-practice example for other hospitals.

Installation of the new LED lighting

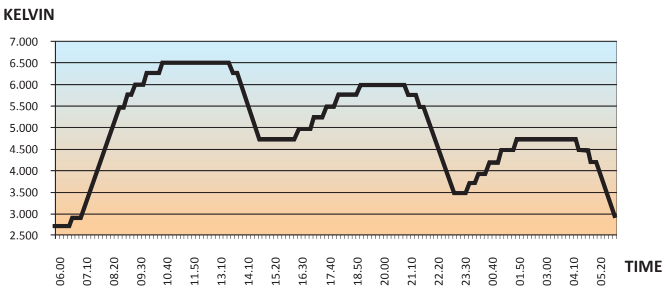
The new LED lighting

The old LFL lighting

Much better spectrum with LED lighting



Daily Human Centric Lighting variation



Best Practice example:
Higher lighting quality with LED at Nisa hospitals in Spain

Being aware of the importance of lighting for the perception of well-being, the group Hospitals Nisa decided to execute a complete retrofit to use of LED lighting aiming to improve uniformity, lighting levels, efficacy and visual comfort.

The retrofit for the seven hospitals has resulted in savings of around 64% and 2169 tons reduction in CO_2 emission. In particular, a good example was seen in Valencia Hospital, where 8500 light fittings (PLC Downlights, LFL and halogen spots) were upgraded to LED products as well as incorporating levels, DALI control with a payback period only being 0.6 years.

Achieving a pleasant aesthetic environment through using high quality lighting systems is beneficial to aiding patient recovery, as well as contributing to the well-being of staff.

The new LED Lighting

Terminology used in the guidelines

Key Term	Definition
Accent Lighting	Localised highlighting of displayed merchandise or features of a shop or building.
Average Illuminance	The illuminance averaged over an area, measured in lux.
Ambient Lighting	The light surrounding an environment or subject.
Adaptation	The eye's ability to adapt to different light levels.
Accommodate	Adjusting the focal length of the lens of the eye with the purpose of focusing the image of an object – at a given distance – on the retina.
Ballast	Device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current and waveform) for starting and operating, e. g. limiting the amount of current for fluorescent and HID lamps.
Colour Rendering Index (CRI)	A quantitative measure up to 100 Ra (where 100 is the highest) of the ability of a light source to reproduce the colours of various objects accurately in comparison with a reference light source. Light sources with a high CRI are desirable as the colours are more vibrant.
Correlated Colour Temperature (CCT)	Measure to describe the appearance of a light source by defining its colour correlated with the black body locus, measured in degrees Kelvin (K). Colour temperatures above 4000 K appear cool while colour temperatures below 3200 K appear warm.
Contrast	The difference between the luminance brightness of an object compared to that of its immediate background.
Cylindrical illuminance	Total flux falling on the curved surface of a defined cylinder divided by the area of the curved surface of the cylinder. The axis of the cylinder is assumed to be vertical unless otherwise stated. This is a measure of how much light falls on people's faces.
Daylight Factor	The ratio of the illuminance received at a point indoors from a sky with a known luminance distribution (usually an overcast sky) to the horizontal illuminance outdoors from an unobstructed hemisphere of the same sky. The ratio is expressed as a percentage. Direct sunlight is excluded from both values of illuminance.
Diffuse lighting	Lighting that is incident from many directions. Non-directional lighting is normally described as diffuse lighting.
Diffuse ratio	The ratio of the flux leaving a surface or medium by diffuse reflection to the incident flux.
Diffuse Reflection	The process by which incident flux is redirected over a range of angles.
Diffuser	Device to redirect or scatter the light from a source, primarily by the process of diffuse transmission.
Downlighter	Lighting unit which directs the light downward and can be recessed, surface mounted or suspended.
Driver	A unit that is located between the power supply and the LED module(s) in order to provide the LED module(s) with an appropriate voltage and current. The driver is also called electronic control gear.
Flicker	The impression of the rapid and repeated variation with time of a lamp's brightness or (less usually) colour.
Gateway	A device for interfacing between two networks that use different protocols, which may use different data speeds, data voltages and data meaning.
Glare	The discomfort or interference with visual perception upon viewing an extremely bright object against a dark background.
Horizontal illuminance	Illuminance incident on the horizontal surface measured in lux.
Illuminance	The amount of light incident on a surface/plane in lux.
Indirect Lighting	Lighting by luminaires distributing 90-100 % of the emitted light upward.

Key Term	Definition
Lamp	Light emitting device whose performance can be assessed independently and which consists of one or more light sources. It may include additional components necessary for starting, power supply or stable operation of the unit or for distributing, filtering or transforming the optical radiation, in cases where those parts cannot be removed without permanently damaging the device.
LED light engine	The combination of one driver and one or more LED modules.
LED module	A unit supplied as a light source. In addition to one or more LEDs, it may contain optical, mechanical, electrical and electronic components, but excluding the driver.
LED Package	A unit including an optical lens, bonding wire (to bond the package to the printed circuit board), electrodes and resin to encapsulate the LED chip for protection.
Lens	Glass or plastic element used in luminaires to change the direction and control the distribution of light rays.
Lifetime	Measured through a combination of lumen maintenance or light loss and failure fraction or physical failures. Light loss is the reduction in light given out by the device over its lifetime. Failure fraction is the percentage of failures over the lifetime.
Light	Radiant energy that is capable of exciting the retina and producing a visual sensation. The visible portion of the electromagnetic spectrum extends from about 380 to 780 nm.
Light Distribution	The means by which the light is distributed when it radiates from the luminaire or the light source.
Light Source	Surface or object designed to emit mainly visible optical radiation produced by a transformation of energy. The term 'visible' refers to a wavelength of 380 – 780 nm.
Lighting control	Lighting control refers to an intelligent network of devices that may include relays, occupancy sensors, photocells, light control switches or touchscreens, and signals from other building systems (such as fire alarm or HVAC). Adjustment of the system occurs both at device locations, via a wireless unit and at central computer locations.
Louvre	A series of baffles used to shield a source from direct view at certain angles or to absorb unwanted light. Baffles usually are arranged in a geometric pattern.
Lumen maintenance	Percentage decrease in lumen output of a light source over time. Every lamp type has a unique lumen depreciation curve. It compares the amount of light produced from a light source when it is brand new to the amount of light output at a specific time in the future.
Luminaire	An apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes all the parts necessary for supporting, fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply. A 'luminaire' can accommodate one or more 'lamps' or 'light sources'.
Luminaire Efficiency	The ratio of luminous flux (lumen) emitted by a luminaire to that emitted by the lamp or lamps used therein. Can also be expressed as LOR.
Luminance	Photometric measure of the luminous intensity in a specified direction. The SI unit for luminance is candela per square meter (cd/m^2).
Luminance contrast	When an object or surface has a luminance different from the background then there is a luminance contrast.
Luminous Efficacy	Ratio of total luminous flux (lm) to the power consumption (W), lm/W.
Luminous Flux	Luminous flux (in lumen or lm) is a measure of the total quantity of visual light emitted. Radiometrically, it is determined from the radiant power. Photometrically, one lumen is defined as the luminous flux emitted within one steradian by a point source having a uniform luminous intensity of one candela.
Luminous Intensity	The flux per unit solid angle in the direction in question. It is a measure of the amount of light emitted in a given direction.

Key Term	Definition
MacAdam ellipses	The region on a chromaticity diagram which contains all colours that are indistinguishable to the average human eye, from the colour at the centre of the ellipse. The contour of the ellipse represents thus the distinguishable differences of chromaticity (a 1-step MacAdam ellipse). MacAdam ellipses are often scaled up to be e. g. 3, 5 or 7 times the original and called 3-step, 5 step or 7-step MacAdam ellipse. In a 7-step ellipse, the extremes of the ellipse are 14 steps away from each other.
Maintenance factor	Correction factor use in lighting design to compensate for the rate of lumen depreciation, caused by lamp ageing (lumen depreciation and lamp failure) and dirt accumulation (luminaire and environment). It determines the maintenance cycle needed to ensure that illuminance does not fall below the maintenance value.
Overall Efficacy	The light output per unit power taking into consideration both the energy consumed in ON mode plus in STANDBY mode. The overall time period measured must be a minimum of 24 hours, but accuracy improves with longer periods such as a week or a full year.
Photometric Distribution	The photometric distribution is the measurement of light intensities at various angles in absolute units, measured in candelas (cd) and degrees, commonly illustrated via 'light distribution curves' in so-called 'polar diagrams'.
Quality of Lighting	Pertains to the light sources spectral qualities and distribution of luminance in a visual environment. The term is used in a positive sense and implies that all luminances contribute favourably to visual performance, visual comfort, ease of seeing, safety, and aesthetics for the specific visual tasks involved.
Reflectance	Ratio of the luminous flux reflected from a surface to the luminous lux incident on it.
Reflection	Characteristic of a surface's ability to to return (bounce back) light or energy. Various surfaces will reflect light in different ways, i. e.: specular or diffuse surfaces.
Reflector	Device used to redirect the luminous flux from a source by the process of reflection.
Smart lamp	A lamp that can be controlled via a wireless signal using a smartphone, remote control unit or other device. Some smart lamp products are part of a dedicated home automation system including many appliances and an integrated energy management system.
Socket	Component that mechanically and electrically connects the lamp to the luminaire.
Spectral Distribution	A spectral power distribution (SPD) curve shows the precise colour output of a given light source by charting the level of energy present at each wavelength across the visible spectrum.
Spectrum	The visible spectrum is the portion of the electromagnetic spectrum that is visible to the human eye. Electromagnetic radiation in this range of wavelengths is called visible light. A typical human eye will respond to wavelengths from about 390 to 780 nm. The spectrum does not contain all the colours that the human eyes and brain can distinguish. Unsaturated colours including pink or purple variations such as magenta are absent because they can be made only by a mix of multiple wavelengths. Colours containing only one wavelength are also called pure colours or spectral colours.
Standby mode	Mode where the lamp or luminaire is connected to the power source and at least one smart network function is activated. For lighting, STANDBY mode occurs when the lamp/luminaire is turned OFF by the user interface or dimmed to zero visible light but the lamp/luminaire continues to use energy in order to be ready to receive the next wireless communication from the user interface. Testing has established that for lamps where the light can be switched off by an OFF button or dimmed to zero, the STANDBY power is the same.
Task Lighting	Lighting directed to a specific surface or area that provides illumination for visual tasks.
Thermal management	The ability to control the temperature (heat) of the device junctions in the packaged LEDs, often through the use of heat sinks. Junction heat can negatively impact the performance of LED lighting, including output, colour and lifetime.
Troffer	A rectangular luminaire that fits into a modular dropped ceiling (i. e. in Europe 60 by 60 cm luminaires, in the US 2' by 2' or 2' by 4'). Typically, troffer luminaires have been designed to accommodate standard fluorescent lamps (T12, T8 or T5) but are now often designed with integrated LED sources. The term is derived from "trough" and "coffer".

Key Term	Definition
Visual Comfort Probability, VCP	Rating of a lighting system expressed as a per cent of people who, when viewing from a specified location and in a specified direction, will be expected to find it acceptable in terms of discomfort glare. Visual comfort probability is related to discomfort glare rating (DGR).
Work-Plane	The plane on which a visual task is usually done, and on which the illuminance is specified and measured. Unless otherwise indicated, this is in Europe assumed to be a horizontal plane 0.85 meter above the floor.
Workstation	Combination and spatial arrangement of work equipment, surrounded by the work environment under the conditions imposed by the work tasks.

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Premium Light Pro Consortium:

Austria
Austrian Energy Agency
www.energyagency.at

Czech Republic
SEVEn, The Energy Efficiency Center
www.svn.cz

Denmark
Energy piano

Portugal
Institute for Systems and Robotics,
University of Coimbra

United Kingdom
Energy Saving Trust
www.energysavingtrust.org.uk

Germany
co2online gGmbH
www.co2online.de

Italy
Politecnico Milano
www.energia.polimi.it

Spain
Ecoserveis
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