Building Physics

2. Lighting - basics - artificial lighting - daylighting

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Lighting

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For all functions of living and working, good lighting is essential. This does not just concern the amount of light required to ‘perform the task of the eye’, but also the level of visual comfort. It is especially important to prevent major differences in brightness in the field of vision. Furthermore, the lighting must be sufficiently divided or, rather, properly focussed if a certain object must be accentuated. This chapter deals with all basic variables and provides directions for dealing with daylight and artificial light.

4.1 Basic principles

Light as electromagnetic radiation

What we call light is, just as heat radiation, an electromagnetic wave. The difference lies in the wavelength. Radio waves on the one hand and roentgen and radioactive radiation on the other belong to the same physical phenomenon (see figure 4.1). The propagation velocity is the same for all these waves, namely $3 \cdot 10^8$ m/s, in other words 300,000 km/s.

Within the electromagnetic radiation spectrum, it is only wavelengths between 0.38 and 0.78 μm (1 μm = 10^{-6} m) which are visible to the human eye. This is shown in figure 4.1. As the eye's sensitivity to each wavelength is not the same, measuring the amount of energy within the wavelength range of visible light will not do.

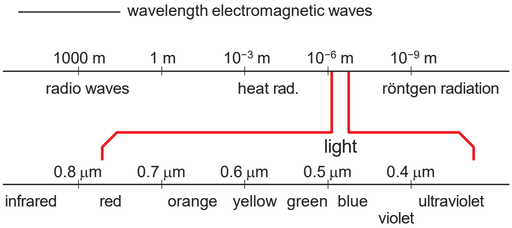


Figure 4.1 Wavelength of electromagnetic waves

wavelength [µm]	eye sensitivity [%]	colour impression
0.38	0.004	
		violet
0.42	0.4	
		blue
0.50	32	
		green
0.555	100	
		yellow
0.59	76	
		orange
0.63	27	
		red
0.78	0.001	

Figure 4.2 Colour impression and eye sensitivity, depending on the wavelength of the light

Relative eye sensitivity is given in the table in figure 4.2 and figure 4.3, for the circumstances that you will face in the field of building physics. It appears that the eye is most sensitive to light with a wavelength of 0.555 μm (yellowish-green).

Luminous intensity and luminous flux

The units in which light is measured were originally laid down on the basis of comparisons of visual clarity, where light was allowed to fall on a particular surface for reference. The strength of light from a given light source was varied (by changing the distance or by filtering) until the same level of apparent clarity was achieved as at the point of the light source in question. The usual light source was a candle of a particular size and composition; the light from a standard candle had a luminous intensity of 1 candela, and created an illuminance of 1 lux on a surface at a distance of 1 m.

It subsequently became the practice to measure light based on the energy generated by the light (the electromagnetic radiation). In addition to the luminous intensity (cd) and the illuminance (lux), the luminous flux (in lumen) is important. The luminous flux refers to the electromagnetic radiation that is perceived as light by the human eye. The starting point for measuring the various lighting units nowadays is the luminous intensity.

The relationship between luminous intensity and luminous flux is defined as follows: 'The luminous intensity (in candela) is the luminous flux (in lumen) transmitted in a given direction per unit of solid angle (steradian).'

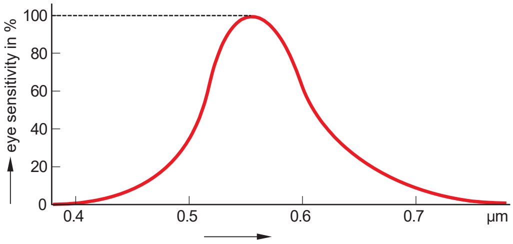


Figure 4.3 Relative spectral sensitivity of the human eye

A solid angle ω is defined as the part of the surface area of a sphere (*A*) divided by the radius squared (R^2). This is illustrated in figure 4.4. The solid angle is expressed in steradians:

$$\omega = \frac{A}{R^2} \text{ [sr]}$$

The solid angle ω does not depend on the shape of the excision that is made on the surface area of the sphere. As the surface area of a sphere equals $4\pi \cdot R^2$, a solid angle that takes up the entire area is equal to 4π steradians.

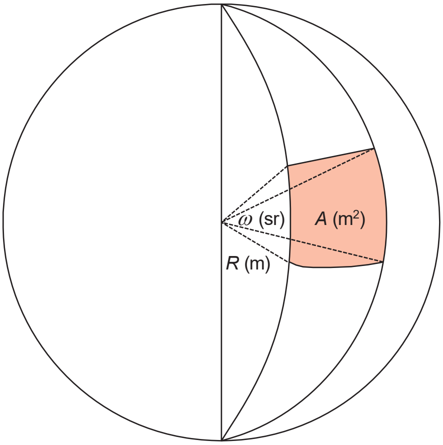


Figure 4.4 Solid angle ω cuts an area *A* of the surface from the sphere with radius *R* around the origin, and is expressed in steradians

From what is stated above, it would appear that the definition describing the relationship between luminous intensity and luminous flux assumes a point-shaped light source. In practice however, all light sources have finite dimensions. This does not form any problems as long as the beam from the 'imaginary' sphere created around the light source is many times greater than the dimensions of the light source.
The relationship between the luminous intensity (*I*) and luminous flux (Φ) can of course also be written differently: 'The lumen is the luminous flux emitted at a strength of one candela by a light source, in a solid angle of one steradian.'
The unit of luminous flux is therefore cd · sr. However, this has been given its own term, 'lumen'.

$$\Phi = I \cdot \omega \text{ [lumen]}$$

If the luminous intensity of every direction of a light source is known, it should in principle be possible to determine the total luminous flux. If the luminous intensity is the same in every direction, the following applies to the luminous flux:

$$\Phi = 4\pi \cdot I \text{ [lumen]}$$

As already stated, the luminous intensity is used as the starting point for the definitions (SI basic unit). The candela is the amount of luminous intensity, perpendicular to the 1/600,000 square-metre surface of a black body, at the solidification temperature of platinum (2042 K), at a pressure of 101,325 Pa. Although the photometric units were originally associated with the above definition of the candela, present-day practice uses a definition based on an energy flow measured in watts, relative eye-sensitivity as shown in figure 4.3 and a 'photometric radiation equivalent' of 680 lumen/watt.

Illuminance

Illuminance *E* is the amount of captured luminous flux Φ per unit of surface area *A*:

$$E = \frac{\Phi}{A} \text{ [lumen/m}^2 \text{ or lux (lx)]}$$

In general, the illuminance – if the distance to the light source is great enough to regard it as a point source – will decrease by the square of the distance (see figure 4.5).

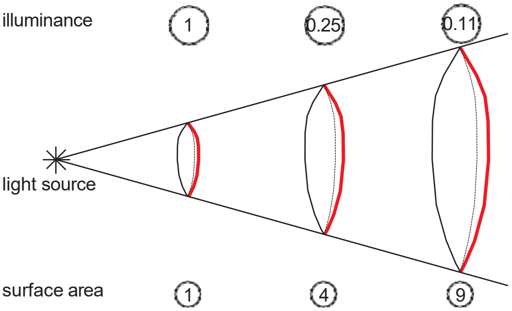


Figure 4.5 The luminous intensity decreases by the square of the distance, when the radiation from a point source (or one that can be regarded as such) is unhindered

At a distance of 1 m, the surface area of an imaginary sphere that is cut out by a solid angle of 1 sr, is 1 m^2 in size. With a luminous intensity of 1 cd (= 1 lm/sr), the illuminance at this point is 1 lm/m^2, or 1 lx. At a distance of 2 m, the same solid angle cuts out a surface area four times as large. The illuminance is then just 0.25 lx, because the same luminous flux passes over a surface area that is four times as large. The angle at which the light hits the surface is also important. If it falls at a non-perpendicular angle it is spread over a larger area. At distance *R* from a light source, the illuminance amounts to the following:

$$E = I \cdot \frac{\cos\theta}{R^2}$$

The meaning of the symbols is:

E the illuminance in lx (lm/m^2)
I the luminous intensity of the source in cd
R the distance to the point source in m
θ the angle of incidence

Clearly, a surface that stretches out, and which is lit by a pointed source, will have a different illuminance at different points, because both the distance from the light source and the angle at which the light hits the surface will vary. It should be noted, incidentally, that the luminous intensity is no indication of the brightness with which a particular surface is observed.

Luminance and brightness

The brightness of a particular surface is a subjective matter, determined by the physiological and psychological circumstances of the observer. The variable 'luminance' (*L*) was introduced in order to express the relationships governing brightness, etc. (see figure 4.6):

$$L(\theta) = \frac{I(\theta)}{A \cdot \cos\theta}\ [\mathrm{cd/m^2}]$$

The meaning of the symbols is:

$A \cdot \cos\theta$	the 'apparent' surface of surface element *A*
$I(\theta)$	the luminous intensity as emitted by a surface element *A* in the direction of θ

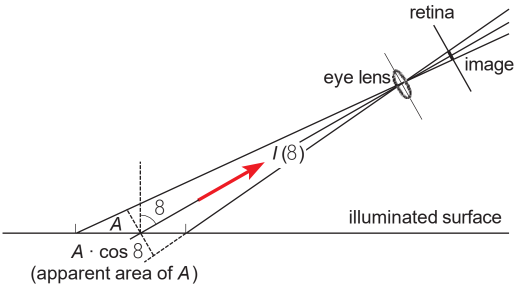


Figure 4.6 Luminance of an illuminated surface depends on luminous intensity $I(\theta)$, surface element *A* and angle θ

An image forms on our retina on which the surface is in proportion not just to the distance with the illuminated surface, but more especially with the 'apparent' surface of element *A*:

$$A_{\text{apparent}} = A \cdot \cos\theta$$

The luminous flux that forms the image on the retina is in proportion with the illuminance emitted and the distance of the eye from surface element *A*.

The number of lumen received per m^2 of retina does not depend on the size of the surface element *A* and its distance from the eye. After all, if the size of the surface element is halved, the luminous intensity that is emitted, in other words the luminous flux in lumen per steradian, is twice as small. Given that the image on the retina is also twice as small, the number of lumen received for each m^2 of retina remains the same.

If the distance between the eye and the surface element is doubled, the illuminance that is emitted by the surface element will be four times less at the location of the eye. As the image on the retina is also four times smaller, the luminous flux (in lumen) that is picked up by the eye again remains the same per m^2 of retina. This all applies to the luminance defined above, but for practical purposes is just as relevant to the subjective aspect of brightness.

The terms brightness and luminance are often mixed up. However, when quantifiable variables are under discussion, luminance should always be used.

Surfaces reflecting or radiating diffused light

A surface radiates diffused light, if the luminance on every point of the surface is the same in every direction. A surface can transmit light through heat (burning steel plate), through transmission (opal cover for a lighting fitting or ornament) or through reflection of incident light. In the case of reflection, the surface radiates diffused light regardless of the angle of incidence of the incident light. Surfaces on which this may occur, to a greater or lesser degree, include plasterwork, gypsum, and new concrete – in contrast to a mirror on which the angle of incidence of light is the same as the angle of reflection. Hybrids are also possible (see figure 4.7).

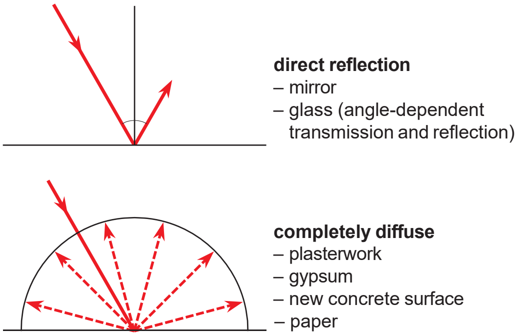


Figure 4.7 Targeted and diffused reflection of light

The luminance of surfaces reflecting diffused light can be easily calculated from the illuminance if the reflection coefficient of the surface is known.

$$L = \frac{r \cdot E}{\pi} \; [\mathrm{cd/m^2}]$$

The meaning of the symbols is:
L the luminance in $\mathrm{cd/m^2}$
r the reflection coefficient
E the illuminance in lx

This formula clearly illustrates that luminance and illuminance are totally different variables. As has already been explained, the illuminance is determined by incident light. The surface on which the light falls is totally irrelevant. The luminance of a surface – what we perceive – is on the one hand dependent on the illuminance of the surface and on the other, the characteristics of the surface, such as the reflection factor. Different surfaces have different luminances, even where the illuminance is the same.

The table in figure 4.8 shows the reflection factor for a number of materials. It goes without saying that the reflection factor does not have to be the same for all wavelengths. If this were the case, then with incident white light the surface would become more and more grey with a lower and lower reflection factor, until black at $r = 0$.

surface/colour	**reflection factor**		
	light	***medium***	***dark***
white	0.80	0.70	-
grey	0.60	0.35	0.20
black	-	-	< 0.04
yellow	0.70	0.50	0.30
beige	0.65	0.45	0.25
brown	0.40	0.20	0.07
red	0.35	0.20	0.10
green	0.50	0.25	0.12
blue	0.55	0.25	0.08

white plasterwork (new, dry)	0.70-0.80
white plaster work (old)	0.30-0.60
brick (new)	0.05-0.15
brick (old)	0.10-0.30
concrete (new)	0.40-0.50
concrete (old)	0.05-0.15
aluminium, high-reflection	0.80-0.85
aluminium, matt	0.50-0.60
dark wood varieties (iroko, wengé)	0.10-0.30
light wood varieties (birch, light oak)	0.30-0.50
writing paper	0.70-0.80

Figure 4.8 Numerical values of the diffuse visible light reflection coefficients of a number of surfaces of various materials

A surface only reflecting light of a certain wavelength will show just this colour when it is illuminated by white light. For instance when red light strikes a green surface this will show black because it reflects only green light.

Colour temperature

Colours and their associated wavelengths are given in figure 4.1. All colours together, as in sunlight, are perceived as being white. This also applies to the light given out by incandescent lamps, for example, although sunlight appears whiter than the light from lamps. This depends on the extent to which the various wavelengths are represented in the spectrum. Like the sun, incandescent lamps emit thermal radiation. As was explained in the chapter on heat radiation, all objects emit radiation. With low temperatures this is only heat radiation or infrared radiation, but when temperatures are higher, it also includes visible light and ultraviolet radiation. In the case of the temperature of the surface of the sun (on average, about 5750 K) the peak of the radiation is located in the middle of the field of visible light. As temperatures fall, the peak shifts to where there are longer wavelengths, the red area, and the light becomes more yellow in colour. With incandescent lamps (2700–2900 K), the peak of the radiation curve is actually outside the range of vision.

The radiant temperature is a measure for the ‘ambience’ of white light. Fluorescent lamps and LED lights do not emit thermal radiation and therefore often have a spectrum that is very different to that of an incandescent lamp. In principle three colours (red, green, blue) are enough to create white light. Modern LED lamps however use more colours. Nevertheless, a radiation temperature is used in order to be able to indicate the colour of the light. This is what is known as the added colour temperature. Descriptions of the light colours, with their associated temperatures, are as follows:

- 2500–2900 K: extra warm white
- 2900–3300 K: warm white
- 3300–5000 K: (neutral) white
- > 5000 K: cool white

The added colour temperature is determined by comparing the light from the lamp in question with the light from a black body. The temperature at which the light colour of the black body most closely corresponds to the light colour of the lamp in question is referred to as the ‘added’ colour temperature. However, the colour temperature gives no indication about the colour rendering of the light of the lamp in question. An object of a particular colour can only be seen, after all, in that colour if the colour is sufficiently represented in the light directed at it. Different fluorescent and LED lamps can have a different spectrum even with the same added colour temperature, and therefore have different colour rendering.

Colour rendering index and luminous efficacy

When deciding upon a light source, there are two areas that are important: the quality of the light and the level of energy consumption. The luminous efficacy provides information on the latter. This is calculated by dividing the total luminous flux by the amount of input energy. The luminous efficacy is therefore expressed in lumens per watt (lm/W). Apart from the efficacy of the light source, the features of the fitting and the location (colour of the walls, ceiling, etc.) are important factors in determining the eventual energy consumption for illuminating the building. This is covered below.

The colour rendering index R_a was introduced to properly describe colour rendering. The index shows to what degree the colours of a number of sample objects being lit by the light source under investigation correspond with the colours of the same objects under the light of a reference source, under strictly prescribed circumstances.
For light sources with an added colour temperature of 5000 K, the reference light source is a black body radiator with a temperature that is the same as the added colour temperature of the light source being tested. Above 5000 K, a reference light source has to be used with a spectral energy distribution that corresponds with CIE (Commission Internationale de l’Eclairage) standard daylight D.

The general colour rendering index is determined from the degree of colour shift that occurs with eight sample colours. It can be supplemented with the colour shifts of another six sample colours – it may be possible for the individual colour rendering index to be given for one or more of the total of fourteen samples. If the colour rendering indices of two light sources correspond, but the added colour temperature does not, the colour rendering in itself may well differ. When comparing two light sources, it is therefore important always to consider both variables.

The maximum value of the colour rendering index is $R_a = 100$. This is the case if there is no colour shift at all. The colour rendering index of incandescent lamps is usually fairly close to the maximum – they emit, after all, thermal radiation. Very high values can also be attained with fluorescent and LED lamps as well. Very high colour rendering ($R_a > 93$) is often at the expense of a certain amount of efficiency, for example because more fluorescent layers need to be introduced for fluorescent lights, which layers hinder each other's transparency.

There are therefore always three matters which determine the choice of lamp:

- the light output in lumen per watt;
- the (added) colour temperature in Kelvin;
- the colour rendering index including a picture of the light spectrum.

4.2 Artificial lighting

Required levels of illuminance

In international and Dutch standards recommendations relating to illuminance for a large number of spaces are given. The table in figure 4.9 gives a general indication for the level of lighting required for carrying out various tasks where good vision is important.

All kinds of illuminance levels can be found in the home. For reading with an extra lamp, values of 250–500 lx are not uncommon, while what is referred to as 'atmospheric lighting' will often not be any more than 50 lx. Values that generally suffice for performing certain tasks like reading, working with one's hands, and so on, can be worked out from the table in figure 4.9.

Calculating illuminance

The light output of every type of lamp is known. Figure 4.10 shows that the 'efficiency' of fluorescent lamps and led lamps especially is much higher than that of incandescent bulbs for example. The use of these lamps is therefore encouraged by the government and the use of incandescent lamps is discouraged. The table lists the light efficiency (luminous flux) in lumen per watt for the total lighting system plus any ballast. The values in the table provide a global indication of the light efficiency to be expected. There are considerable differences for each type and size of lamp and each product, which makes it important to request all the necessary information.

The life expectancy is expressed in burning hours. For certain types of lamps, life expectancy is often defined as the point at which the light output of a given group of lamps has fallen by 30%, either through deterioration or cessation of function. In the case of incandescent and compact fluorescent lamps with integrated electronic ballasts, it is usually the point when 50% of the lamps in the relevant group no longer work.

The level of illuminance that is present in working areas is affected by many factors. First, the fitting in which the lamp is housed. The fitting has a certain luminous efficacy, but also distributes the light in various directions.

The shape of the room in which the fittings are located is therefore also an influencing factor, as of course are the colours (reflection characteristics) of the ceiling, walls and the floor.

The features of the fitting and the room are summarised in what is called the luminous efficacy – see the table in figure 4.11. The table shows that fittings with almost identical fitting efficacies sometimes have very different

nature of the activities	recommended average levels of illuminance
orientation lighting	
● observing large objects and movement of persons (storage areas, car parks)	50 lx
● observing basic details and recognising persons (corridors, staircases)	100 lx
lighting in the work place	
● observing basic details (building site, smithy, warehouse)	200 lx
● reading and writing, comparable details and contrasts (offices, classrooms)	400 lx
● observing finer details and subtler contrasts (drawing office, detailed editing work)	800 lx
special work lighting	
● observing very fine details on a dark background (precision work, cadastral drawing work, close inspection work)	1600 lx
● observing at the limits of visual scrutiny (microminiaturisation, operating theatres)	> 3200 lx

Figure 4.9 Recommended average levels of illuminance for general lighting in various spaces, ranked according to the nature of the activities being performed there

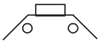
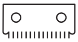
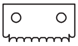
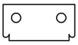
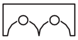
type of lamp	system output [lm/W]	life expectancy [burning hours]
incandescent lamps	6-19	1000-3500
halogen lamps	12-25	2000-3500
fluorescent tubes	65-105	6000-12,500
compact fluorescent lamps	25-80	6000-10,000
led lamps	60-120	15,000-25,000
super high-pressure sodium lamps	30-50	8000
high-pressure mercury lamps	32-57	7500
high-pressure sodium lamps	50-86	6000
low-pressure sodium lamps	72-173	12,000
induction lamps	65-70	60,000

The bottom four lamp types are not suitable for indoor lighting; they are intended for outdoor lighting purposes, such as for public spaces, etc. Here too, led lamps are applied increasingly more often.

Figure 4.10 Light output (luminous efficacy) and life expectancy of various types of lamp

luminous efficacies as a result of the way they distribute the light. It can also be seen that a high fitting efficacy does not necessarily lead to a high luminous efficacy.

The luminous efficacy is greater in larger rooms than in smaller ones. If there is a lot of direct light (mirror optics), the influence of the reflections off the walls of the room is less than that of fittings that give off more diffused light. In general terms it can be said that the luminous efficacy shows the relationship between the average illuminance at the actual work location and the installed luminous flux in lumen per m^2 of floor surface. To make lighting calculations, please refer to the relevant manuals.

				luminous efficacy			
				*small room (h = 2.7m) shape index = 1**		*large room (h = 2.7m) shape index = 3**	
type of fitting			*efficacy of fitting*	*low** reflection*	*high** reflection*	*low*** reflection*	*high*** reflection*
a		beam	0.96	0.27	0.46	0.50	0.70
b		trough	0.81	0.40	0.51	0.65	0.73
c		laminated grid	0.59	0.34	0.41	0.49	0.55
d		prism cover	0.57	0.34	0.40	0.48	0.53
e		opal cover	0.54	0.24	0.32	0.39	0.46
f		mirror optics	0.56	0.36	0.42	0.49	0.53

* shape index $k = \frac{l \cdot b}{h(l + b)}$ where: l = length of the room, b = width of the room, h = distance from the fitting to work location

** low reflection factors: ceiling -0.3; walls -0.1; floor -0.1

*** high reflection factors: ceiling –0.7; walls –0.5; floor -0.1

Figure 4.11 Standard values for the luminous efficacy for various types of fittings in different-shaped rooms with different reflection characteristics

NB: Higher efficacies are obtainable with modern mirror-optic fittings than those shown in the table.

Differences in brightness

Too large differences in brightness can lead to problems (such as dazzling) when work is being performed, while if the differences are too small the surroundings will be dull, at least from a visual point of view. For that reason, it is recommended to keep the levels of luminance in the immediate vicinity of the working area in proportion. If the luminance ratio is greater than 10:1, the room will look unsettling, but if the ratio is less than 3:1, it will seem monotonous.

The luminance of the surface directly in the eye's vision and that of the immediate surrounding area, in other words of a piece of paper and of the desk on which the paper is lying for example, should preferably not differ by more than a factor of 3. Within the normal field of vision, the luminance ratio limit should be a factor of 10, although for areas located outside the direct field of vision, a factor of 20 should be the maximum (see also the table in figure 4.12).

Proper light fittings ensure that dazzling is prevented by covering the lamp.

luminance ratio	subjective perception of contrast
1	none
3	easily visible
10	considerable
30	too great
100	much too great

Figure 4.12 Subjective perception of contrast (differences in brightness)

As an illustration, examples are given in figure 4.13 and 4.14 of dazzling caused by unprotected fluorescent lamps and the impossibility of distinguishing details due to too great differences in luminance. In the last case (a person in front of a window) the brightness of the window will have to be reduced (with blinds or curtains), or the person lit up by turning on the lights in the room.

Colour and colour rendering

For a comfortable indoor environment it is important that the colour of the artificial lighting is appropriate to the luminous intensity. This is also the case with daylight. The greater the luminous intensity, the more preferable it is to opt for a higher colour temperature. In spaces without daylight with an illuminance of less than 500 lx, lamps with a low colour temperature (< 3300 K, warm white) are best. For illuminance levels of between 500 and 1000 lx, or for combinations of daylight and artificial light, lamps with a colour temperature of around 4000 K (white) are the most suitable. Light sources with a high colour temperature (> 5000 K, cool white) should only be used where there is a high level of illuminance. The suggested values for the colour temperature and colour rendering index in a number of situations are given in the table in figure 4.15.

Colour rendering indices can be qualified as follows:

- R_a = 90–100: good
- R_a = 80-90: sufficient
- R_a = 50-80: moderate
- R_a = < 50: poor

Heat development through light

In general only a very limited proportion of the electricity that is fed to a lamp is actually converted into light. The largest share is immediately released as heat (radiation and convection), such as with spot lamps. The light, too, is converted into heat after it has been absorbed by the objects and walls in the room. Fluorescent lamp ballasts also give off a limited amount of heat.

Figure 4.13 Too great differences in brightness caused by unprotected fluorescent lamps

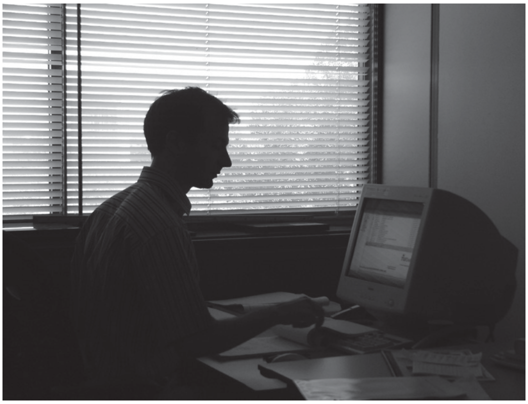


Figure 4.14 A person in front of a brightly lit window appears only as a silhouette

All the energy that is supplied eventually ends up as heat in the building. In large factories and office buildings this can be as much as around 15 (it used to be 25 to 35) watts per m^2 of the floor surface. Together with the heat emitted by office equipment and solar radiation this represents a heat burden that often has to be removed through mechanical ventilation. To prevent this, or at least to restrict it, and also with a view to making savings on the electrical energy that is used for

examples of locations and activities	recommended colour temperature [K]	minimum desirable colour rendering index [R_a]
offices, shops, schools and sport halls with extended combination of daylight and artificial light	4000	80*
offices and shops where only a small amount of daylight is present; covered swimming pools	< 3300	80
houses, schools and meeting places in hospitality establishments and social and cultural locations	< 3300	80
areas where medical research is performed	4000	90
industry		
• workshops in clothing factories	4000	80
• assembly halls, lathe workshops	4000	50
• foundries, rolling mills	-	-
assessing colour slides in the graphic industry	4500/5000	90
assessing colours in the textile, paint, foodstuffs and graphic industries	7400	90
locations where people move from one place to another, halls, staircases	< 3300 or 4000**	50 of 80**

* For school classrooms where drawing and painting are taught, a value of $R_a > 90$ is recommended.

** These values should be adapted to the other light sources in the building.

Figure 4.15 Suggested values for colour temperature and colour rendering index in sample situations

the lighting itself, it makes sense to be as careful as possible about using lighting. Normal, low-energy lighting equipment has an installed capacity of approx. 10 W/m^2. It does not need to be any higher than this. With the help of ‘workplace lighting’ or more ‘localised’ general lighting it is possible (in specific cases) to go back to 6 to 8 W/m^2. In buildings with a mechanical ventilation installation, the air is often sucked away through the lighting fittings, so that a significant proportion of the heat is removed directly from the room. This is also favourable for the luminous efficacy as it helps cool the lamp.

4.3 Daylighting

Availability of daylight

The amount of natural light available during normal working hours is rarely sufficient for the recommended illuminance levels mentioned in section 4.2. Outside illuminance levels vary during the course of the day, and can change even for a short period of time, as a result of cloud movements, thunder storms, etc. Research has shown during what percentage of the time at least a certain level of illuminance is present in an outdoor open space. This is shown in figure 4.16. Between 8.00 hrs and 16.00 hrs the illuminance outside, in an open space, is more than 6000 lx for 90% of the time.

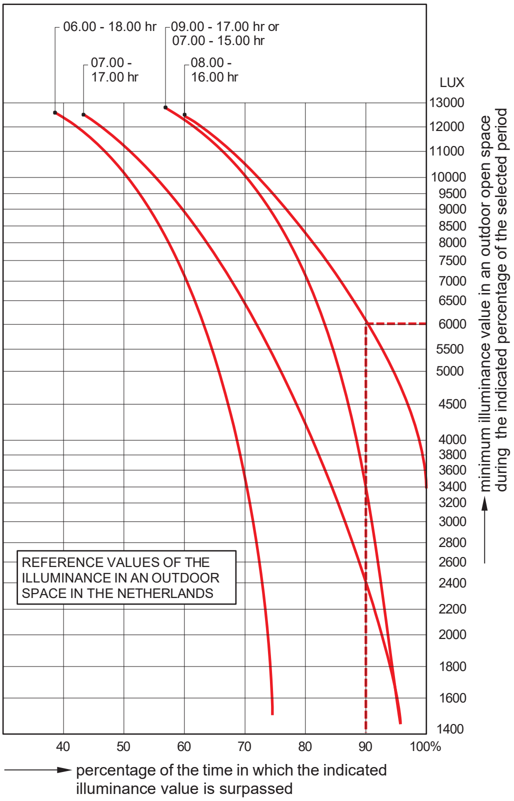


Figure 4.16 Illuminance in the free field outdoors

Daylight factor

For the purposes of lighting a space during daytime it can now be required that there be a minimum level of illuminance during a certain period of the day (during working hours, for example). Clearly though, it will not be possible to reach this minimum level with daylight throughout the whole year. During winter, with its short days, or when there is very thick cloud cover, artificial light will be needed. To determine the level of illuminance through daylight, the so-called daylight factor is used.

The daylight factor is defined as the relationship between the illuminance indoors and the illuminance outdoors in an open space, at the same time. If the former is 150 lx and the latter 5000 lx, the daylight factor would be as follows:

$$\frac{150}{5000} \cdot 100\% = 3\%$$

If the outdoor level rises to 10,000 lx, the illuminance inside rises to 300 lx. The daylight factor remains the same.

Example

An illuminance level of 300 lx is required in a workshop for 90% of the time between 8.00 hrs and 16.00 hrs. From the graph in figure 4.16, it can be seen that the outdoor illuminance is greater than 6000 lx for 90% of the time during that period. The daylight factor required in the workshop is then:

$$\frac{300}{6000} \cdot 100\% = 5\%$$

To achieve a given daylight factor various matters have to be taken into consideration, including the size of windows, the interception of light by protrusions from the building (canopies, for example) or indeed other buildings, the transparency of the glass and blinds if present, dirt on the windows, the reflection of light by the interior walls, floor and ceiling in the room (a white wall is a better reflector than a coloured one), and so on. It should also be borne in mind that the spatial distribution of daylight from the sky differs from one direction to another.

The calculations for determining the daylight factor assume a cloudy sky, as the strength of the sun is too changeable as a source of light. As far as the sky is concerned, the starting point is generally a distribution of luminance levels laid down by the CIE (Commission Internationale de l'Eclairage), based on research by Moon and Spencer, where the luminance in the zenith (perpendicular) is three times greater than that on the horizon.

Various measurements have shown that, for the Netherlands, this distribution is a reliable approach for most cloud-cover situations. It is only when there are very heavy, low clouds that the distribution is more appropriate to a uniform sky: a luminance level that is the same over the whole sky.

Sky component

The most important aspect of the daylight factor is the sky component. This is the direct light from the sky reaching the point under consideration after it passes through the window opening. It is initially calculated without the reduction caused by glass or blinds (d_h^*).
The sky component therefore primarily depends on the part of the sky that is seen through the window. It is converted into a measurable unit through a projection on a horizontal plane (see figure 4.17).
This projection can be made with the help of a radial diagram. (You can find a radial diagram on www.klimapedia.nl together with other diagrams for personal use.) Entry variables for this are the angles from which the daylight opening in question are seen (see figure 4.18).

Eindhoven University of Technology has developed a diagram that can be used in combination with the radial diagram. This daylight diagram is divided up into a large number of sections, all of which contribute equal amounts (0.1%) to the illuminance on the horizontal plane.
There are two versions of the diagram: one for a uniform sky, and one for a sky with a CIE luminance distribution.

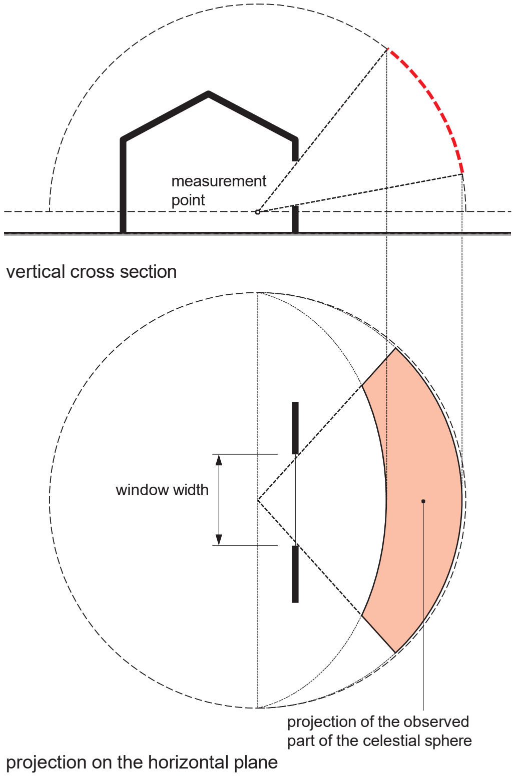


Figure 4.17 Principle for determining the sky factor

A random window and skylight have been entered onto the radial diagram in figure 4.19. With the help of the daylight diagram for a uniform celestial sphere, the number of sections can be counted (including half sections as much as possible). Around 48 sections are counted for the window, and about 62 for the skylight. This means a sky component (without losses caused by glass) of $d_h^* = 4.8\%$ and $d_h^* = 6.2\%$ respectively.

If the diagram with the CIE distribution is used, the result is $d_h^* = 3.9\%$ and $d_h^* = 7.1\%$ respectively. It is a coincidence that the totals are identical. However, it is clear that in using this division of luminance, the contribution of the skylight is greater, and that of the window is smaller.
There are of course a number of computer programs which let you determine the daylighting without using diagrams. A well-know program is ‘Dialux’ which can be downloaded free of charge. However, the diagrams provide good insight into the matters at play and remain useful for a quick judgement on the daylighting situation.

External reflection component

To work out the external reflection component (d_e^*), it is in principle necessary to determine the luminance of all the surfaces that are capable of reflecting the daylight towards the light opening under consideration. The contribution made by these reflections to the indoor illuminance should then be calculated. This is a very time-consuming task and difficult to conduct to precision. For that reason, the following approach will suffice (and also because the contribution to the total daylight factor is usually fairly slight).
It should be stated that the luminance of any obstacles that are visible through the light

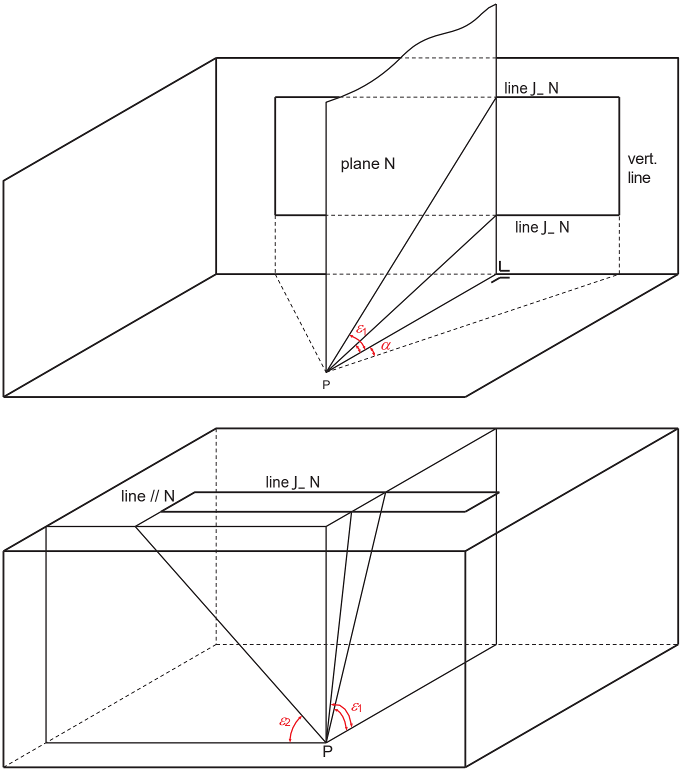


Figure 4.18 Calculating the azimuth (α) and elevation (ϵ) of the outer parameters of surface for projection in a radial diagram

opening from the measuring point is about 15% of the luminance of the sky located behind these obstacles. This means, then, that the external reflection component can be determined, with the help of the diagrams, by working out the sky component of the part of the sky that is blocked from view by the obstacles, and multiplying the result by 0.15:

$$d^*_e = 0.15 \cdot d^*_h$$

Here, d^*_h is the sky component (without losses through the presence of glass) of the part of the sky that is not visible.
If the surrounding buildings reflect very strongly (due to their light colour) a slightly higher 'reflection' value than 15% can be used. However, it is often worthwhile in such cases to take the trouble of making a more accurate calculation. A light floor finish can also make a contribution to the indoor illuminance, through reflection off the ceiling for example. Usually, though, this contribution is negligible.

Losses in the light opening

Glass (or other material) and sun-blinds in the light opening will reflect and absorb part of the incoming light. The LTA factor (absolute light entry factor) indicates which part of the incoming light ultimately ends up in the room. For single and double glazing these are:

- LTA = 0.85 to 0.90, single glazing
- LTA = 0.70 to 0.80, double glazing
- LTA = 0.70-0.80 HR^{++} insulation glazing
- LTA < 0.70 solar control glass

A reduction factor c_k, to be used if there are any railings in front of the window, or if the window itself is partitioned, can be determined from the ratio between the nett glass surface area and the area including the railings, partitions, etc. If not enough is known about the frame, the following value can be used:

$$c_k = 0.85$$

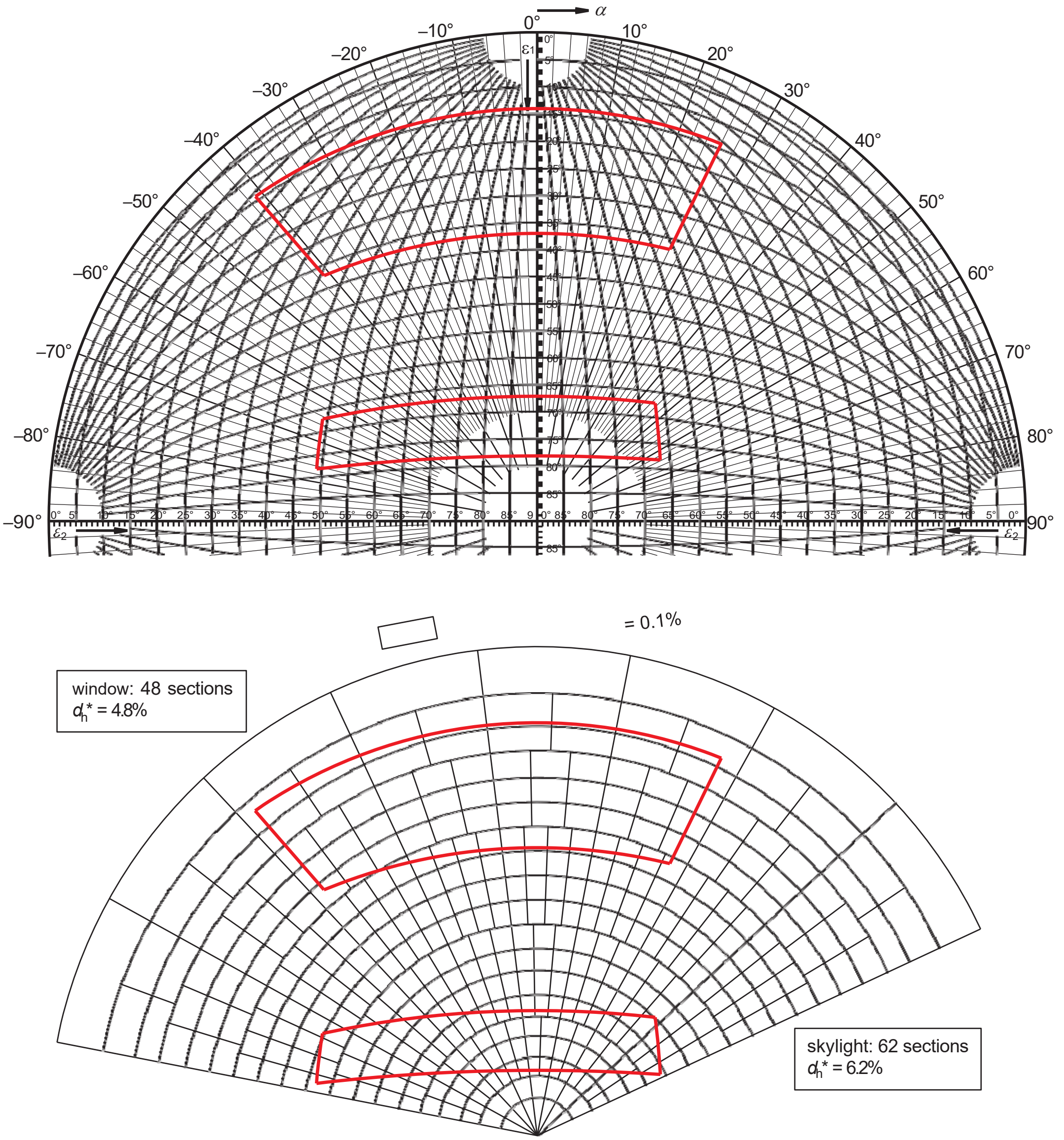


Figure 4.19 Window and skylight entered into the radial diagram and a diagram for calculating the sky component, where there is an even spread of luminance (uniform sky)

Transparency can be reduced further by dirt, to a level 0.9 to 0.5 times the value of a clean surface:

$$c_v = 0.9 \text{ to } 0.5$$

Based on the above, the total level of loss in the light opening is denoted by factor c:

$$c = \mathrm{LTA} \cdot c_k \cdot c_v$$

Internal reflection component

When light falls upon a surface in a room, the surface will, depending on its characteristics, in turn reflect some of the light, thereby contributing to the illumination of other surfaces (including working surfaces) in the room. The calculations involved here are complex. Luckily, there are computer programmes in existence for working out internal reflections, the resulting luminances of the various surfaces in the room and the level of illuminance of working surfaces.

To gain an impression, without having to make any calculations, of the size of the internal reflection component (d_i), the table in figure 4.20 can be used. This gives the d_i components in percentages for various reflection factors for walls, floors and ceilings (see also the table in figure 4.8), based on an average situation for losses in the light opening and any possible obstacles, assuming the presence of single-glazing.

glass area as proportion of floor area [%]	reflection factor of walls			
	20%	*40%*	*60%*	*80%*
10	0.2	0.3	0.6	0.9
20	0.3	0.6	1.1	1.7
30	0.5	0.9	1.5	2.4
40	0.6	1.2	2.0	3.1

The reflection factor of the ceiling is about 70%, and that of the floor, around 20%.

Figure 4.20 Internal reflection component, in percentages, of various wall-finish reflection factors

When other types of glass are used, whether with sun blinds or not, the figure from the table should be corrected using the actual LTA. The table applies where LTA = 0.9. For HR^{++} glazing the correcting-factor is for example: $LTA_{dg}/LTA_{eg} = 0.75/0.9$ = approx. 0.85.

If the calculation appears to show that the contribution of d_i is a decisive element in the total daylight factor, then it is worthwhile to make an accurate measurement of the internal reflection component.

Determining the daylight factor

The daylight factor can be found by adding up the calculated components mentioned above:

$$d = d_h + d_e + d_i \text{ or}$$

$$d = (d^*_h + d^*_e) \cdot c + d^*_i \cdot \frac{LTA}{0.9}$$

The meaning of the symbols is:

d^*_h	the sky component without losses caused by the presence of glass
d^*_e	the external reflection component without losses caused by the presence of glass
c	the reduction factor for losses in the light opening ($c = LTA \cdot c_k \cdot c_v$)
d^*_i	the internal reflection component from the table in figure 4.8, including average losses in the daylight opening, with a light entry factor of LTA = 0.9

Daylight requirements for homes and other buildings

Dutch building legislation includes requirements for light entry for residences, in the form of an equivalent daylight surface area. This is defined in the standards indicated in the building regulations.

As is usual, legislation assures a certain minimum level of quality. Building design, however, involves more than simply applying the rules, and that is certainly the case as far as windows are concerned. As well as light entry, appearance is also very important.

It should also be remembered that large glass surfaces, conservatories, atria and skylight domes cause a significant flow of heat into buildings whenever the sun shines on them. This leads to welcome energy savings during the winter, but in the summer it can cause the indoor temperature to rise to sometimes unacceptably high levels. However, this can be prevented if the building is designed properly (effective summer ventilation, sun-blinds, etc.).

Incoming sunlight can also cause problems through large differences in brightness, particularly for people working with documents, on drawing tables, and so on. For that reason, some type of sun-blinds will often be necessary.