PREFACE

Lighting takes a very significant part of the energy used in buildings. In Adelaide (South Australia) office buildings this is as much as 35%, whilst in London (where the heating requirement is much greater) it is still over 23%. If we want to practise and create Passive and Low Energy Architecture, the 'passive' lighting, ie daylighting gives the second largest opportunity (after HVAC; heating, ventilating, air conditioning) for energy conservation.

It has been observed that in warm climate buildings, especially schools, the concern for reducing solar heat gain leads to the overdesign of shading devices. In a classroom with 60% glazing of its long walls often there is no view other than the inside of the shading device, consequently there is no daylighting to speak of, so electric lights are on all day. The reason for this is that many architects do not know how to design a device which does the job, but not more, which is just right. They want to 'be on the safe side' and overdesign the shading, completely forgetting about daylighting.

Good daylighting in a building will not just happen. It has to be carefully designed. And this design is not just the sizing of windows. Daylighting considerations must be included in the earliest architectural decision-making process, concerning issues such as building massing, orientation or depth-to-height ratios.

This is why after three Notes on thermal issues, the present Note 4 is devoted to daylighting.

The Note has two aims:

1. to provide an understanding of the physical facts involved: the sun as a light source, the sky as a luminaire and fenestration as the facilitator/controller of the light – at the conceptual level, which should influence the early architectural decisions
2. to give a working method for the detail design of fenestration, including sizing, to ensure the adequate provision of daylight.

As glazing is an essential element of daylighting, the plan is to have the next Note (Note 5) devoted to Glass, comfort and energy. It is at this level that lighting, thermal and energy issues converge.

The Editor would be grateful for any comments, observations or suggestions. As this is not a commercial publishing venture, we would like you, the reader, to become part of the process of producing these Notes. It is not a money-making exercise, we consider it as a service to the profession, to students and to the 'cause' of passive and low energy architecture. Please send such communications to the address below, where these Notes can also be ordered.

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# DAYLIGHTING

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INTRODUCTION

Lighting is one of the most important requirements of interiors, as the visibility of the environment is an essential condition of our activities. There are two possibilities to meet the demands – with daylight or with electric lighting – the two options are not equivalent.

Electric lighting of interiors can be designed for a set quantity and quality, but daylighting offers the following advantages:

- The quality of daylight is better, (in spite of the fact, that it is continuously changing), as human vision developed under natural lighting.
- Its quantity allows higher illuminance levels than what is practicable with electric lighting, at least during daytime, for a considerable part of the year. We may enjoy an illuminance of 1000 lux or larger in rooms where the illuminance by electric lighting would be only 200-300 lux.
- Daylighting is provided by renewable energy: daylighting is the most obvious and friendliest use of solar and sky radiation.
- The luminous efficacy of daylight is very good, only the best electric light sources can compete with it.
- Well designed daylighting can meet the required illuminance in 80-90% of the daylight hours, so it allows the saving of a considerable part of the energy that would otherwise be consumed by artificial lighting.
- Daylighting is more than just lighting, ie making the environment visible. It ensures a connection with the external environment, external radiation and sky conditions, thus it satisfies a psychological need.
- The continuous changing of the quantity of daylighting (provided that it is not too severe) is favourable as it has a stimulating effect.
- Adequate or generous provision of daylighting of a dwelling may increase the market value of that dwelling.

There are consultants available for electric lighting design, but the design of daylighting is usually the task of architects. Designing of daylighting needs a considerable expertise. The present note intends to introduce the reader to the essential characteristics of daylighting and the factors to be considered in daylighting design:

- the sources and features of natural light
- different openings and their characteristics
- the characteristics of daylighting produced by different openings
- the connection between external conditions and internal lighting
- how lighting requirements may be met
- a method of design for the most common cases.
Symbols and abbreviations

- **a**: width of room (m)
- **A**: relative area of the window (%)
- **ARw**: required relative area of the window (%)
- **ALT**: solar altitude angle (°)
- **AZI**: azimuth angle (°)
- **b**: depth of room (m)
- **d**: length of the light's path through the opening (m)
- **DF**: daylight factor (%)
- **DF_{av}**: average value of daylight factor on the work plane (%)
- **DF_{min}**: minimum daylight factor on the work plane (%)
- **DF_{p}**: daylight factor at point P (%)
- **DF_{R}**: required average daylight factor on the working plane (%)
- **DF_{R\text{min}}**: required minimum daylight factor on the working plane (%)
- **E_{e}**: illuminance from the sky on a horizontal unobstructed surface (lx)
- **E_{e\text{d}}**: design external illuminance (lx)
- **ER**: required average illuminance on the work plane (lx)
- **E_{5}**: illuminance from the sun on a horizontal unobstructed surface (lx)
- **E_{F}**: area of opening through which the light penetrates to interior (m²)
- **E_{h}**: headroom (m)
- **INC**: angle of incidence of light beam (°)
- **K**: luminous efficacy (lm/W)
- **L**: luminance (cd/m²)
- **L_{Z}**: luminance of the zenith (cd/m²)
- **L_{θ}**: luminance of sky at θ angle above horizon (cd/m²)
- **m**: height of opening (m)
- **p**: width of window or toplight (m)
- **q**: height of window or length of toplight (m)
- **r**: height of working plane above the floor (m)
- **S_{awR}**: required area of window (m²)
- **S_{TR}**: required area of toplight (m²)
- **t**: length of time during a day or a point in time (h)
- **T**: length of time during a year (h/year)
- **T_{c}**: correlated colour temperature (°K)
- **ZEN**: zenith angle (angular zenith distance) of the sun (°)

- **α**: orientation or azimuth angle of a point of sky (°)
- **γ**: horizontal angle of obstruction (°)
- **δ**: slope of opening (°)
- **ε**: vertical angle of obstruction (°)
- **θ**: altitude angle above horizon (°)
- **η_{o}**: efficiency of the opening (-)
- **κ**: angular distance of a point from the sun (°)
- **λ**: wavelength (nm)
- **ρ**: reflectance (-)
- **ρ_{c}**: reflectance of ceiling (-)
- **ρ_{f}**: average reflectance of floor (-)
- **ρ_{g}**: reflectance of ground (-)
- **ρ_{o}**: average reflectance of obstruction (-)
- **ρ_{tw}**: reflectance of toplight's wall (-)
- **ρ_{w}**: average reflectance of walls (-)
- **τ**: transmittance for parallel light (-)
- **τ_{diff}**: transmittance for diffused light (-)
- **Φ**: luminous flux (lm)
- **Φ_{e}**: radiant energy flux (W)
- **Φ_{ext}**: luminous flux incident on transparent surface of the opening (lm)
- **Φ_{int}**: luminous flux entering the interior through an opening (lm)
- **ψ**: uniformity of illuminance on the work plane (-)
1 LIGHTING REQUIREMENTS

The goal of lighting is to produce an adequate visual environment. An environment is adequate if it ensures visual comfort and if it serves the visual tasks required by the function of the room. Visual comfort is a condition of mind expressing satisfaction with the visual environment.

An interior space meets these requirements if its parts can be seen well without any difficulty and the given visual tasks can be performed without strain. Visual comfort may be ensured to different degrees and at different levels. Visual comfort is a function of the whole visible environment. Together with thermal and acoustic comfort, visual comfort is a contributor to the overall comfort sensation.

Serving the visual task required by the room's function means that lighting makes the details of the reference plane visible correctly, quickly and free from discomfort. This requirement normally relates to a horizontal work plane, to a well defined given part of the environment.

Lighting has to provide general visual comfort at all times, and additional requirements beyond this may have to be met for specifically defined functions.

The following characteristics are generally specified for providing suitable visual environment in everyday practice:

• average illuminance on the working plane
• uniformity of illuminance on the working plane
• luminance ratios within the room
• the allowable level of glare
• the direction of light and the effect of shadows
• colour temperature and
• colour rendering qualities of the light.

The level or quantity of the above depend on the requirements defined by the room's functions.

The question 'How far can the requirements of lighting be met with natural lighting?' can be answered only with full knowledge of the natural light source and the circumstances determining the changes of natural lighting.

2 SOURCES OF NATURAL LIGHT

As various lamps are the sources of light in electric lighting, so the sun is the source in daylighting. Its light arrives into the interior space directly or indirectly, scattered in the atmosphere and reflected by surfaces in the natural or artificial environment.

As a luminaire filters and distributes the light emitted by the electric lamp within it, so the luminaire of daylighting is the exterior space which lets the sun's light into the interior space by transmitting, scattering or reflecting it. This includes the sky, as well as the natural and man-made external environments; all parts of the environment the room can 'see'. Consequently the sun, the sky, the surface of the earth, plants, other buildings may all serve as parts of the "natural luminaire". The function of these elements in daylighting may vary widely from time to time and from one case to another.
In one extreme case there is no obstruction in front of the opening, and daylighting comes from the sun, the sky and the ground. Another extreme case is a built up area, where the sky and the ground may not be seen from the room, so daylight is a result of light reflected from the buildings standing opposite.

The sun, the sky, natural obstructions (plants, the terrain) and artificial obstructions (buildings, constructions) contribute to a varying degree to the natural lighting of interiors. This degree keeps changing partly due to the sun's movement and changes of cloud, and partly because the plants’ foliage and the ground's reflection change with the seasons (eg due to snow cover).

Daylighting is based on solar radiation, which reaches the outer limits of earth's atmosphere in amounts that slightly change seasonally according to the sun-earth distance. The average value of extraterrestrial solar irradiance (the 'solar constant') is 1353 W/m², and the correlated colour temperature of the light is 5760°K. At the earth's surface this change is much more dramatic.

The sun, as the light-source determines the essential characteristics of the available natural light, the length of the days and its seasonal changes, as well as the character of changes during the day. These characteristics are dependent on the earth's movement and the angle of the earth's axis. Because of these, the characteristics of the natural light-source depend also on geographical location.

The total irradiance at the earth's surface is irrelevant from the point of view of daylighting, as only a part of it is at visible wavelengths. What is relevant is that part of the irradiance (the total solar flux) which is in the visible range of the spectrum. It is illuminance on an unobstructed horizontal surface that can be used to measure the quantity of available natural light.

2.1 Characteristics of sunlight

Direct solar radiation may reach the earth's surface, but part of it is absorbed passing through the atmosphere and it may be obstructed by clouds.

Direct sunlight is characterised by:
- its continually changing direction,
- its probability of occurrence,
- the illuminance (the luminous flux incident on a unit surface) it creates on an unobstructed horizontal surface,
- its correlated colour temperature $T_c$ (the temperature of a black body, at which the spectral distribution of its radiation is nearly the same as that of the given light) and
- its luminous efficacy ($K$), (with an electric lamp this is the ratio of the luminous flux it produces to the rated electrical input, here it is the ratio of (visible) luminous flux to the total energy flux) in both cases lumen/W.

The direction of the sun's radiation may be characterised by the angles of solar azimuth (AZI) and altitude (ALT). The variations of these angles are depicted by sun-path curves on a sun-path diagram. Each sun-path curve refers to two days of the year (except the shortest and the longest day).
Such diagrams are valid for one particular geographical latitude.
For a more detailed discussion see PLEA Note 1: Solar geometry.

Fig. 2.2 Sunpath diagram (for latitude 48°, the Northern hemisphere.)

The probability of sunshine duration is the function of the clouds to be expected, and it also depends on the geographical location. It may be well characterised by sunshine duration expected at 50% probability. This is the so-called probable value of sunshine. The 50% probability of sunshine in each hour can be represented on a sunpath diagram, which gives a good indication of sunshine during the year (Fig. 2.3).
The values of illuminance created by the sun on an unobstructed horizontal surface ($E_s$) may vary between 0 and approx. 100,000 lux, depending mainly on solar altitude and cloud cover. The probable values of $E_s$ during the year can well be illustrated by an isopleth diagram. Its curves show the points of time when $E_s$ exceeds certain values at 50% probability. These curves can be read in a way similar to level contour lines on a map. The area inside each contour shows the period of the year in which external illuminance from the sun ($E_s$) is greater than the value indicated by that contour.

Fig.2.4 Points of time when solar illuminance ($E_s$) exceeds the values indicated. (example for Hungary, - latitude 48°, northern hemisphere)
The correlated colour temperature ($T_c$) of direct sunlight is about 3000°K when the sun is near the horizon, and about 5800°K when it is near the zenith. The luminous efficacy ($K$) of sunlight depends on the solar altitude. Its value starts at zero at the horizon, and it uniformly increases until $\text{ALT} = 20^\circ$. Over this angle its value is some 105 lm/W.

The use of direct sunlight for natural lighting is limited by the following circumstances: Sunshine may only be expected in part of the period between sunrise and sunset, because of obstruction by clouds. For example in Europe this fraction is between 20% and 70% of that possible. Because of the continuous movement of the sun, insolation of an interior depends on the relative position of the sun and the opening. For example, in a given location, during a 14-hour clear day the period of insolation is:

- 12 hours, through a window oriented to the equator,
- 7 hours, through a window oriented east or west,
- 2 hours, through a window of polar orientation,
- 14 hours, through a horizontal opening.

Direct sunlight illuminates only a part of the room in any case. There is a sharp dividing line between the sunlit part and the rest of the room. The sunlit area is highly illuminated in contrast to the rest of the room. For this reason, the illuminance of the interior is very irregular and the large luminance contrast may cause glare.

If the sun is visible from the room and it is in the field of view of occupants, it causes severe glare. Because of the undesirable effects of direct sunlight on the visual environment, direct sunlight is acceptable only in a few cases. At places of work, where the use of the room is defined, direct sun penetration is to be avoided during working hours. If the use of the room is undefined, eg in a corridor or a living-room, insolation may be allowed from time to time, or permanently. Thus the use of direct sunlight for the natural lighting of interior spaces is rather limited. In most cases we have to provide protection against the discomfort effects of direct sunlight.

2.2 Characteristics of diffuse sky light

The atmosphere of the earth is comparable to a hemisphere of a more or less translucent material which is transilluminated by nearly parallel beams of sunlight. The central point of this hemisphere is always the point considered in the room which it illuminates. Considering that the dimension of the atmosphere is much greater than the dimension of a room, any point of the room may be considered the centre of the hemisphere. The transparency of every element of the surface of the hemisphere changes continuously.

One extreme possible sky condition is a totally clear, cloudless sky. This corresponds to a transparent hemisphere that disperses light only to a small degree (this scatter causes the sky to appear to be blue; without it it would be black). Another extreme possible sky condition is a uniformly overcast sky which corresponds to a translucent hemisphere that disperses light to the highest degree. All other sky conditions may be regarded as transitional between these two extremes. Either the cloud cover gets thinner and thinner, or parts of the sky are clear and other parts are overcast. Fog is another condition of the sky, when the clouds extend to the ground.
While sunshine passes through the atmosphere

- it is scattered by gases, water vapour and particulates and
- its spectral composition changes.

These effects depend very much on the condition of the sky. If the sky is absolutely clear, scattering is relatively small, the quality of light strongly differs from that of the sun, the sky appears as blue. If the sky is overcast, scattering is very strong, the quality of light is only slightly different from that of the sun: colder. The term 'grey sky' describes this condition.

The luminous flux ($\Phi$) (the part of radiation that produces a visual sensation) reaching the earth's surface from the sky depends very much on the solar altitude and on sky conditions. Changes of the atmosphere are depicted by meteorological-statistics. Characteristics of diffuse (sky-) light change accordingly. The amount of natural light available at a given place, at a given time of the year changes from year to year. Consequently, it can only be characterised by a probability value.

This may be one of the extreme values or that with a 50% probability, referred to as the expected value. These are lighting-meteorological characteristics. The sky as a luminaire can be described by
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- its luminance distribution or
- the illuminance created on an unobstructed horizontal plane
- the length of time during which daylight may be used
- by the colour temperature of light (T_c) and
- the luminous efficacy of the light (K)

From the point-of-view of quality the sky may be characterised by its luminance distribution. This can be the basis of calculating its effect inside a room.

Fig.2.7
Luminance distribution of a uniformly overcast sky
\[ L_\theta = L_z \frac{1 + 2 \sin \theta}{3} \]

Fig.2.8
Luminance distribution of a foggy sky
\[ L_\theta = \text{constant} \]

Fig.2.9
Luminance distribution of a clear sky
\[ L_\theta = L_z \frac{1 - e^{-0.32 \frac{0.91 + 10e^{-3\kappa} + 0.45 \cos^2 \kappa}{\sin \theta}}}{0.274(0.91 + 10e^{-3\text{ZEN}} + 0.45 \cos^2 \text{ZEN})} \]

where \( L_z \) is the luminance at the zenith, \( \theta \) is the altitude angle of the point considered above the horizon, \( \kappa \) is the angular distance of this point from the sun and ZEN is the sun’s zenith angle.
There are however two problems with this manner of characterisation. On the one hand, there are innumerable possible distributions and only three of them can be described by a mathematical formula; on the other hand, the values of luminance are statistical variables, so its values with a given probability may be a result of measurements over several years. Such a collection of data has only been started at a few locations. These automatic sky scanners collect data of 145 elements of the sky every few minutes.

Despite these problems, this manner of characterisation is very important, as it enables us to define two extreme and an intermediate sky condition as illustrated by the above three diagrams (Figs. 2.7, 8 and 9).

These functions give only ratios, not absolute values. They show that:
- the zenith is three times brighter than the horizon if the sky is overcast, but constant in azimuth
- the brightness of the sky is uniform in foggy weather independent of direction
- the brightest parts of the sky are around the sun (circumsolar radiation) and at the opposite side (90° from the sun's direction); the horizon may be brighter than the zenith if the sky is clear.

The luminance of the sky depends on the solar altitude, both when the sky is overcast and when the weather is foggy. Thus the sky is darker in the morning than at noon and it is lighter in summer than in winter. These distribution functions are important as with their use two extreme and an intermediate sky condition may be determined. If we know the sky luminance distribution, \([L(\theta, \alpha)]\), the illuminance of an unobstructed horizontal surface \((E_e)\) can be calculated.

\[
E_e = \int_0^{360^\circ} \int_0^{90^\circ} L(\theta, \alpha) \sin \theta \cos \theta \, d\alpha \, d\theta
\]

Fig. 2.10 Illuminance from the sky (integrated from horizon to zenith and for the whole horizontal circle)
The sky, as a luminaire may be characterised as a first approximation by the illuminance on an unobstructed horizontal surface $E_e$, the external illuminance.

This manner of characterisation is not as exact as the former one, as it disregards the area of origin of light in the sky. The same external illuminance may be created by an overcast or a foggy sky, while the horizon is darker when the sky is overcast than when it is foggy. Consequently, the illumination of the interior will be different in these cases.

In spite of this, this manner of characterisation is widely used because of its simplicity: one number instead of 145 data points. Its inaccuracy is negligible compared to this advantage and it can be corrected to satisfy practical needs.

Reliable values of the external illuminance $E_e$ may be provided by many (15–20) years of data collection. Measured illuminance data are few and far between, but such values of the external illuminance may be estimated with reasonable accuracy from meteorological solar radiation data. This gives a considerable practical benefit, as solar radiation has been measured and recorded in many places, for decades.

The daily changes of $E_e$, the external illuminance, can be depicted by a distorted sine curve.

The amplitude of the sine curve is proportionate to the sun's altitude at noon. So the smallest curve indicates the shortest day and the largest curve the longest day of the year. The above figures show that the external illuminance is highly variable: ranging over ±50% about the 'expected' values.

The expected value of $E_e$, the external illuminance may be illustrated by an isopleth diagram (Fig.2.12). It is similar to Fig.2.4, but that showed sunlight illuminance ($E_s$), this one shows skylight illuminance only ($E_e$).
(Its curves show the points of time when $E_e$ exceeds certain values at a 50% probability. The area inside a curve shows the period of the year in which external illuminance ($E_e$) is greater than the value denoted by that curve.)

The duration-- (or daylight availability--) curve tells us what portion of the year we may expect various $E_e$ illuminance values.

![Duration curve of illuminance from the sky ($E_e$). (Hungary, latitude 48°, northern hemisphere)](image)

Daylight is available for some 4400 hours a year between sunrise and sunset. The quality of daylight first of all depends on the condition of the atmosphere. The correlated colour temperature of the light ($T_c$) of an overcast sky changes between 4500 and 7000°K, but the light of a clear sky may be 10 000--40 000°K. With intermediate sky conditions the correlated colour temperatures may be expected between the above values. The luminous efficacy ($K$) of daylight depends to a lesser extent also on solar altitude. Its value varies between 115 and 130 lm/W.

The sky as a luminaire is further characterised from the point of view of illuminating interior spaces:

- The sky surrounds buildings as a hemisphere, so the use of its light may only be reduced (during daytime) by an external obstruction.
- The illuminance created in interior spaces by diffuse sky light is generally free from excessive contrasts, (as with sharp boundaries of sun-lit areas), consequently it does not cause glare. The sky, when seen from the interior space, only rarely causes unpleasant glare.
- Skylight is available continuously and safely during the day.

For all these reasons the sky plays a decisive role in daylighting.

### 2.3 Environmental influences

The environment, both its natural and man--made components, may play a role in the illumination of interior spaces by reflecting skylight and sunlight. In this way, it plays a passive role. The quantity and the periodic change of light reflected from the environment are basically determined by the light arriving from the sun and the sky. The reflectance of the environment has a secondary effect on the amount of available light, but the colour of the surfaces of the environment may modify the quality of reflected light to a large degree.
DAYLIGHTING

A part of the natural or built environment seen from the interior is either 'ground' or an obstruction, if it blocks out a part of the sky or the sun. This can be determined in relation to a given point of the working plane of a given room. For example, the same building may be partly an obstruction for a point of a room and partly ground.

![Diagram of daylighting](image)

Fig. 2.14 The effect of an obstruction on daylighting

The effect of an obstruction on illumination is twofold: it blocks out the contribution of part of the sky and it may also exclude direct sunlight some of the time. On the other hand, it may reflect light from other parts of the sky (or from the sun) into the room.

![Diagram of obstruction dimensions](image)

Fig. 2.15 Dimensions of an obstruction
DAYLIGHTING

Depending on the geometry of the position of a given external surface, it may present a different obstruction when viewed from different parts of the room.

An obstruction of a given point may be characterised by (see Fig. 2.15):
- the solid angle subtended by it at the point considered
- or approximately by the \((\gamma_1 \text{ and } \gamma_2)\) horizontal and \((\varepsilon)\) vertical angles which form its boundary viewed from the point and
- by its average reflectance \((p_0)\)

The effect of the ground on daylighting is of secondary importance, because its light may only reach the working plane after repeated reflections. It is characterised by its reflectance.

3 OPENINGS

Natural light enters the room through transparent surfaces. These may be windows or other openings which involve transparent elements. An opening is always a constructional part of the building and in addition to its function in daylighting, it has to meet a number of other requirements. Its main purpose may be daylighting, but its form is influenced by other essential considerations.

Such an opening may be a window, a skylight or roof-window, a transparent wall or a ceiling as well as any other transparent part of the envelope. From the point of view of lighting such constructional elements have three parts: namely
- transparent elements,
- structural obstructions and
- light-reflecting surfaces.

Openings are characterised from the point of view of natural lighting by the following attributes:
- location,
- nominal dimensions,
- angle of slope and orientation,
- the form of light transmission (direct, diffuse),
- character of distributing light in space,
- efficiency and
- their ageing.

In addition to these, the possibility of visual connection with the environment is a very important quality.

An opening may be either in a wall or in the roof.

The nominal dimension of an opening is the dimension within the surface of the envelope element which incorporates it as a constructional unit.

In side-lighting, the size of the transparent surface may not be much smaller than the nominal opening, in top-lighting, however, the size of the transparent surface may be far smaller than that of the opening.

The slope of opening \((\beta)\) is the angle between the transparent surface and the horizontal plane, and the orientation of the opening \((\alpha)\) is the angle between the surface normal of the transparent surface and the north, measured in a clockwise direction (i.e. the azimuth angle of the surface normal).
The efficiency of openings.

The efficiency of the opening \( \eta_o \) is the ratio of the luminous flux entering the interior and the luminous flux incident on the outer surface of the transparent material of the opening. This indicates the efficiency, or the resultant transmittance of the opening.

There are materials the transmittance of which reduces over time. These effects result in the ageing of openings and in reducing their efficiency. Originally clear glass may become translucent because of such effects.
3.1 Sidelights

The transparent surfaces of *sidelights* are almost always vertical, (their slope is $\delta = 90^\circ$), but their orientation is optional. Their location limits the possibilities of their forms. Sidelights may be windows, doors, or fixed transparent parts of walls.

Their transparent surfaces may be transparent or translucent glass (clear-, opal-, sand blasted-, or ornamental glass), glass blocks, profiled glass, etc. The construction of windows is essentially determined by their functions other than lighting (thermal insulation, noise insulation, visual connection, etc.)

The lighting characteristics of sidelights vary, influenced by
- the quality of glass,
- the number of layers,
- dirtiness of the glass,
- their location, form and relative size,
- their construction,
- the thickness of the surrounding wall and the manner of connection,
- their orientation.

An important feature of the illuminance distribution of side-lighting is that it rapidly decreases as we move away from the window. In side-lighting, the degree of possible insolation depends on the orientation of the window.

#### 3.1.1 Windows

The efficiency of illumination depends mainly on the glazing, the number of its layers, the construction, the thickness of the wall surrounding the window and on its cleanliness. The efficiency of ordinary, clear 2–5 m² double glazed windows set in 350 mm walls is between 0.4 and 0.5. A reduction of efficiency may be expected with a greater wall thickness or pollution. Commonly, reduction due to thicker walls may be about 10% and due to pollution it may amount to 30%.

The effect of various constructions on the above efficiency is about ±15 – 20%. The efficiency of windows increases to a small degree with increased size.
3.1.2 Transparent walls

The efficiencies of transparent walls in clean condition are:
- in single clear glass 0.7
- in double clear glass 0.6
- in glass block 0.3
Pollution may reduce these values by 25–30%.

3.2 Toplights

Roof windows or skylights are characterised by the fact that they are located above the plane of the ceiling. Theoretically the size of such roof-lights is only limited by the size of the ceiling.

The slope of a transparent surface (\( \theta \)) may vary between 0 and 90° and its orientation is optional. The transparent material may be clear or translucent to a varying degree.

The form and construction of roof lights may vary greatly. These determine both their light distribution and their efficiency. Two forms may be distinguished: linear and localised openings. Linear roof-windows or skylights are characterised by the following:
- the ceiling opening is rectangular, and its length is several times greater than its width
- their vertical section is constant along their length.

Localised openings are characterised by the fact that the ceiling aperture is a square, a circle, a symmetrical polygon or some other non-elongated form.

3.2.1 Linear toplights

![Fig. 3.7 Illuminance distribution by linear toplights](image)

The most common type of linear toplights can be grouped on the basis of their geometrical form:
- sawtooth
- horizontal
- monitor
- pitched.
DAYLIGHTING

Within each group the sections are similar, thus the lighting provided by them is also similar. They usually provide natural lighting for the interior placed in several, parallel rows. As a consequence, toplights may obstruct each other, thus limiting the direct effect of the sky. In monitor, horizontal and pitched types the obstruction is mutual.

Sawtooth type toplights

These are characterised by a typical sawtooth section. They have one transparent surface, the slope of which is theoretically optional, but in practice, it is generally not less than 45°. The usual material for their transparent surface is clear glass or glass that disperses light to a small degree. In slopes smaller than 90° safety-or wired glass is used. In sawtooth toplighting, illuminance distribution by the typical section is asymmetrical. The forms of reflecting surfaces do not affect the character of distribution significantly. Illuminance along their length changes only to a small degree.

Depending on glazing, their efficiencies are:
- at a 90° slope 0.1 - 0.2
- at a 60° slope 0.2 - 0.25
- at a 30° slope 0.3 - 0.4

An advantage of sawtooth type toplighting is that sun penetration may be eliminated with polar orientation, if the angle of slope is not less than the highest possible solar altitude angle at the given geographical location. This advantage is usually exploited in practice where glare is to be avoided.

Horizontal type toplights

In formal terms they are characterised by curved (barrel vault-type) transparent surfaces, which can "see" practically the whole sky. Their transparent material is a clear or translucent plastic material, occasionally safety glass. In horizontal toplighting illuminance distribution in cross-section is symmetrical. Illuminance along their length changes only to a small degree. Their efficiency is between 0.25 and 0.45 depending on the transmittance of the transparent material.

The quality of lighting is influenced more by the characteristics of the transparent material than by its form.

With clear transparent materials beam solar radiation may enter. It is very difficult to provide protection against it, without unduly reducing daylighting. If a translucent material is used, sunlight may penetrate in diffused form, without casting sharp shadows.

Monitor type toplights

These are characterised by two transparent surfaces joined by an opaque (roof-) structure. The angle of slope of the transparent surfaces is usually greater than 60°. They may be symmetrical or asymmetrical.

The material of the vertical transparent elements is usually normal clear glass, in other slopes wired glass or safety glass.

Illuminance distribution in the sectional plane is symmetrical, if the monitor itself is symmetrical. Illuminance along the length changes only
to a small degree. Depending on their form and glazing, their efficiency varies:

- in symmetrical, vertical glazing 0.1 – 0.2
- in asymmetrical, vertical glazing 0.15 – 0.2
- at other slopes the expected value is greater.

Beam solar radiation would penetrate, and it cannot be eliminated by orientation. Solar protection must be considered as a separate issue.

**Pitched type (linear prismatic) toplights**

These are characterised by two sloping symmetrical transparent surfaces that can 'see' essentially the whole sky. The angle of the slope of their transparent surfaces is generally about 45°. The material of the transparent elements is usually wired glass or, in some cases, safety glass.

Illuminance distribution in the sectional plane is symmetrical. Illuminance in the longitudinal direction changes only to a small degree.

Their efficiency depends mainly on the glazing material, and it is expected to be between 0.3 and 0.4. Solar radiation would penetrate with this type of toplighting with any orientation and protection against it is rather difficult.

### 3.2.2 Localised (spot-) toplights

The most common forms of these are:

- dome
- pyramid
- prism.

These may be located in the roof singly or many of them in a regular pattern. Their effect on each other and mutual obstruction is negligible.

**Dome type toplights**

They are characterised by the fact that their prefabricated (often monolithic) transparent component sits on the usually circular or square framing within the roof structure. The material of this transparent component is clear or translucent plastic.

With units circular in plan the illuminance distribution is symmetrical around a vertical axis in all directions and it has multiple axes of symmetry in square plan toplights.
Fig. 3.12 Illuminance distribution by a pyramid toplight

Their lighting characteristics are mainly determined by the transparency of the dome, and by the form and reflectance of the building fabric surrounding it. Their efficiency is expected to be between 0.2 and 0.4, depending on the above factors.

Fig. 3.13 Illuminance distribution by a dome toplight

In clear dome toplights, beam solar radiation may penetrate, limited by the well effect (the ratio of depth to the opening width). Solar protection must be considered as a separate issue.

If the dome is translucent, sunlight penetrates in diffuse form.

Pyramid type toplights

These are of a pyramidal form, which is made up of four transparent coincident triangles. The angle of the slope of transparent surfaces is usually 45°. The transparent material is usually wired glass, but it may be a monolithic plastic element.

Their illuminance distribution is symmetrical along several planes containing the vertical axis. Their lighting characteristics are determined by the transparency of glazing, as well as by the geometrical ratios and reflectance of the adjoining building construction. Their efficiency is 0.25 - 0.35, depending on the above factors: the greater the angle of slope, the lower the efficiency. If a transparent material is used, beam sunlight penetration is restricted only by the well effect.
Prism type toplights

These are similar to sawtooth toplights in form, the only difference being that their plan is a square rather than elongated oblong.

They are similar to sawtooth toplights also in their construction.

Illuminance distribution in the cross-sectional plane is similar to that of sawtooth lights and symmetrical in the other direction.

Fig. 3.15  Illuminance distribution by a prismatic rooflight

Their efficiency is lower than that of similar sawtooth roof-lights. Polar orientation would eliminate beam sunlight penetration, except in summer early morning and late afternoon.
4 UTILISATION OF NATURAL LIGHT

The daylighting of interior spaces is utilising natural light. Both the quantity and quality of daylighting is influenced by direct sunlight, diffuse skylight, the external environment and the architectural design of the interior. Direct sunlight, the diffuse light of the sky, the natural and artificial external environments are given. The architecturally created interior space and fenestration must respond to these.

In daylighting design the interior space and its fenestration has to be fitted into the given exterior so that its natural lighting meets existing requirements. This can be achieved only if the characteristics of the given external environment are known and it is understood how the form and characteristics of the interior space affect natural lighting. The designer should also be aware of what the possibilities and limitations of natural lighting are.

Daylighting is influenced by the following specific features of the interior:
- location of the opening,
- slope and orientation of the opening,
- construction of the opening and
- size and reflectances of the opening structure.

4.1 The effect of opening location

The essential goal of illuminating the interior is to provide adequate illuminance on the work-plane. Most commonly, the plane of desk-tops is used as a working plane: a horizontal plane about 850 mm above the floor.

The position of the opening relative to the work-plane may vary depending on where in the building the room is located. In the majority of cases, when the room is bounded by walls and ceiling, the opening will be part of the walls or the ceiling, accordingly it is referred to as side-lighting or top-lighting. In cases, where there is no sharp boundary between walls and ceiling, this distinction may be blurred. Openings are thus either sidelights or toplights. Sidelights are usually windows.

Illuminance of a given point of the working plane depends on the location of the opening for the following reasons:
- Openings of the same size may appear to be larger or smaller depending on their relative position and on where they are viewed from. The larger the opening looks from a given point, the greater portion of the sky (the external environment) will contribute to the illumination of the point, and the greater the illuminance of the point.
- The illuminance of a surface depends on the angle of incidence of light. The greater the angle of incidence, the smaller the illuminance.

The result of these effects is that an opening provides maximum illuminance for a point of the work-plane if it is just above it. Consequently, there is a great difference in efficacy of side-lighting and top-lighting: top-lighting is 3 - 5 times more effective than side-lighting.

The placing and orientation of the opening will determine which parts of the external environment may become an obstruction and which parts are 'ground'.
4.2 The effect of slope and orientation

It depends on the slope and the orientation of an opening to what degree the various elements of a given exterior space (e.g. the sun, the sky, the natural and the artificial environment) contribute to the natural lighting of the interior. The slope and orientation of an opening jointly determine the solid angle of the external environment that may be seen from the interior. This is what illuminates the room directly.

The sunpath curves of summer and winter solstices indicate which part of the sky the sun moves in during the year. The slope and the orientation of an opening determine which part of the sky may be seen from the interior. These two together determine whether and for how long the interior can receive direct sunlight. At low- to mid-latitudes the smaller the slope of an opening, the longer the expected duration of insolation. Insolation is largest through horizontal openings and smallest through vertical openings (for a given orientation). At high latitudes an equator-facing vertical plane may receive more irradiation.

A window with equatorial orientation (northern hemisphere AZI=180°, southern hemisphere AZI=0°) receives most, and one with polar orientation the least solar irradiation. The duration of insolation decreases gradually (at a given slope) as the orientation moves away from the equator.

One effect of the slope is that whilst horizontal openings (δ=0°) 'see' the whole sky hemisphere, with vertical (δ=90°) openings, only half of the sky hemisphere may contribute to the illumination of the interior. The amount of diffuse sky light decreases as the angle of the slope increases.

The sky effect is influenced by orientation as diffuse radiation is asymmetrical. This asymmetry may be calculated on the basis of annual radiant energy incident on vertical planes of different orientations. The degree of asymmetry may be expected to be between -20 and +50% from the average value.

The diffuse light of the sky is greatest for an equator-facing orientation. There is no great difference among east, west or polar orientations.

The orientation and the location within the interior in relation to the opening determine which parts of the external environment act as obstruction.

The degree to which the ground influences the daylighting of an interior depends on both the slope and the orientation of the opening. Its slope determines how much ground the interior can 'see'. The more ground it can 'see', the greater the ground effect will be on daylighting of the interior. The ground effect is at its maximum for vertical transparent surfaces (δ=90°). There is no ground effect if the transparent surface is horizontal.

Finally, the deposition of dirt on transparent surfaces also depends on their angles of slope. The smaller the angle of slope, the greater amount of dirt the surface will gather in a given time (the cleansing effect of rain is also reduced), and the more its transparency and efficiency is reduced.
Fig. 4.1 The effect of orientation and slope of opening on defining the effective part of the sky (this example refers to latitude 48°, the northern hemisphere)

4.3 The effect of framing

The structure of an opening connects a single or multi-layered transparent element to the building envelope (wall or ceiling) in such a way that it becomes part of the building, both architecturally and structurally.
Openings can only be evaluated in conjunction with their framing and surrounding structure. With sidelights, the surrounding wall should be taken into account, while toplights should be considered in relation to the ceiling and roof structure.

Fig. 4.2 The effects of structure on utilisable light.

4.3.1 Transparent elements

From the point of view of illumination, the transparent element is the most important part of the opening. It is generally characterised by the following:

- number of layers,
- transparency of the element and
- its transmission/diffusion characteristics.

The number of layers is determined by energy requirements of heating or cooling. If energy demand is small, single glazing is sufficient. If it is large, then double or triple glazing may be used.

Transparency is measured by the $\tau$ transmittance (the ratio of transmitted luminous lux to the incident one). The value of transmittance depends on

- the quality and thickness of the material
- the quality of its surface
- the angle of incidence of light (INC)

For beam sunlight the transmittance of various materials can be calculated by the $\tau$ vs. INC function, such as that shown below (Fig.4.3) for clear glass.

Clear glass is the most commonly used transparent material. Its transmittance is almost constant between angles of incidence of 0° and 60°. It gradually decreases as the angle increases. It is 0 for light parallel with the surface (INC = 90°). Between 2 and 6 mm, the effect of thickness may be ignored in normal clear glass, and the value of $\tau$ may be obtained from the curve given below.
A transparent surface transmits diffuse, multidirectional light, to a different degree from different directions. The transmittance for diffuse light is the weighted average calculated on the basis of angles of incidence and intensity distribution. This is the factor to be used in calculating the effects of sky, ground and obstructions. The value of $\tau_{\text{diff}}$ depends on:

- how much of the sky and ground the transparent surface can see;
- the luminance distribution of the part of hemisphere seen;
- the condition of the sky ($L = f(\alpha, \theta)$), and
- the reflectance of the ground ($p_g$).

Measured values of $\tau_{\text{diff}}$ for normal clear glass may be obtained from the diagram given below (Fig. 4.4).

The resultant transmittance for several sheets of transparent material may be estimated as a product of the transmittances of the individual layers, although this will be slightly smaller than the actual value.

A transparent surface may be clear or translucent from the point of view of light dispersion. Light passes through clear surfaces without changing direction. Consequently, such surfaces do not distort the view of objects seen through them. Translucent surfaces disperse light. As a consequence, the view through such surfaces is fuzzy and objects may not be distinguishable.

Diffusing materials that follow Lambert's law* have the greatest and most even dispersion. For example, opal glass or sandblasted glass. The light dispersion of glass sandblasted on one side is smaller, but it still satisfies practical demands for diffusing glass. Sand blasting both sides of the glass is unnecessary.

A body of material (e.g., a sheet) may be translucent if:
- the material itself is diffusing, such as opal glass;
- the surface is not smooth (it is matt), for example sand blasted glass;
- or if it is structurally heterogeneous or dispersive by its geometry, for example ribbed, ornamental or patterned glass, glass brick, or cellular plastics.

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* A diffusing reflective or translucent material is said to obey Lambert's law if for different directions the transmitted (reflected) intensity (flux per unit solid angle) varies as the cosine of the angle of reflection (measured between the direction of the light wave and the surface normal): $I_\theta = I_\omega \cdot \cos \gamma$. 

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Fig. 4.4 Glass transmittance for components of diffuse light

The transparency of translucent materials varies widely. It greatly depends on thickness if the material itself is diffusive. The thickness of the material does not greatly influence transparency if light dispersion is due to the surface. The value of the transmittance depends on which side light falls on a glass of heterogeneous structure or the dispersion is due to the surface (e.g., glass sandblasted on one side or on a U-profile glass). If one side has a dispersing surface, the transmittance is greater if light is received on that side.

The transmittance differs for parallel and diffuse light also in translucent materials. Unfortunately, only one value of transmittance is normally published, even for widely used translucent materials, and it is not clear whether it refers to parallel beam or diffused light.

If a translucent surface is required, only one layer of the construction needs to be matt. In a combination of clear and sandblasted glass, in most cases the innermost layer should be diffusing.
4.3.2 Structural obstructions

Transparent elements are normally held by some structure or frame that connects them to the wall, ceiling or to some other envelope element of the building. These structures and frames are not transparent. They reduce the efficiency of the opening, to a degree dependent on what proportion of the whole opening they obstruct. The usual relative sizes of the structural obstruction of openings are:

- timber window, single frame, single or sealed double glass 25%
- timber window, double frame, each single glass 35%
- metal window, single frame, single or sealed double glass 20%
- metal window, double frame, each single glass 30%

4.3.3 Reflecting surfaces

The third structural part of openings consists of those opaque surfaces that reflect part of the light entering. The effect of these on the utilisation of light depends on the geometrical proportions of the opening, the reflectance of the surfaces, and the kind of reflection of the surface.

The rays of light that avoid the reflecting surfaces of the opening enter the interior unchanged. The rays of light falling on these surfaces are reflected, suffer a reduction in intensity and change of direction. Even the most reflective surface absorbs part of the incident light.

With reference to Fig.4.5 it can be seen that the greater the distance (d) between the external and the internal side of the opening, the greater the loss of the luminous flux reflected by its surfaces. The smaller the cross-section of opening (F), the greater the loss of the luminous flux reflected on its surfaces. The darker and the more diffusing the surfaces, the greater the loss of luminous flux reflected.

The F/d ratio and the form are important when designing openings. The greater the F/d ratio, the smaller the loss of the luminous flux. The F/d ratio is constant for different light directions only in a few cases. These effects can be summed up by the so called 'well efficiency'. Values of this efficiency are known for simple designs and for constant F/d ratios.

4.4 The effect of the interior

Only a part of the luminous flux entering the room through an opening arrives directly at the work-plane. The rest reaches the work plane only after one or more reflections. This is why the geometry of the interior space, the reflectance of its surfaces and the kind of reflection play a great part in its daylighting.

The degree to which a given surface contributes to illuminating the work-plane depends on its position relative to that plane and to the opening. A given point may receive light from a complete hemisphere. The elements of this hemisphere contribute to the illumination of the point to the degree that they are visible from the point.

The contribution of surfaces to the work-plane illumination depends on how many reflections natural light is subjected to before reaching that plane. Every reflection reduces the amount of luminous flux available. Consequently, the effects of walls, ceiling and floor will differ considerably depending on whether side- or top-lighting is used.
In side-lighting, the effects of the two side walls and the back wall are of primary importance, as they can reflect part of the light entering through the opening to reach the work-plane after one reflection. The effect of the ceiling is smaller, as it cannot 'see' the sky, thus light reaching the ceiling has already been reflected by the ground or by other external surfaces. The effect of the floor is usually negligible, as it is
largely covered by furniture and light reflected from it may only reach the working plane after further reflections. The wall by the window also plays a secondary role only, as light from it has already been reflected at least once (see Fig.4.6).

In top-lighting reflections are less important. The effect of a wall may be significant if it is relatively near the opening, and if it is thus well illuminated, otherwise it plays a secondary role. The ceiling reflects light onto the working plane that has already been reflected on the floor or the walls, so its effect is also secondary. Usually interreflection between the floor, ceiling and work plane is important only as a secondary effect. In this case, furniture also modifies reflection off the floor.

To sum it up, the effect of internal surfaces on daylighting is greater in side-lighting, than in top-lighting.

5 DAYLIGHTING OF INTERIORS

5.1 Lighting systems

There are three systems of daylighting depending on which part of the envelope the light enters the interior, namely
- side lighting,
- top lighting and
- combined lighting.

In combined lighting, there are openings both in the wall and in the ceiling. In an interior where the envelope is not clearly divided into walls and ceiling, e.g. vaulted enclosures, we consider it side lighting if the opening is lower than 2.5m, otherwise it is top lighting.

The illuminance of the work-plane may be direct or indirect. The ratio of light entering directly through the opening and of indirect light reflected from the walls and the ceiling depends on the lighting system, on the location of the opening and on the surfaces of the envelope.

In side lighting, illumination comes from the side, and this is why the illuminance of the work plane near the window is mostly provided by direct lighting. As we move away from the window, the value of direct illumination decreases rapidly, so the relative proportion of the practically constant indirect component increases. The contribution of the indirect component near the back wall may be the same or 2–3 times larger than of the direct.

In top lighting, the work plane is illuminated directly. The proportion of indirect illumination does not normally exceed 25%. In combined lighting, the ratio of the direct and indirect components of illuminance will be between the above-mentioned two extreme values.

5.2 Quantitative treatment of daylighting

Illumination of the interior is quantified by the illuminance on the working plane. This is the most important one in the interior from the point of view of performing work tasks, as demanded by the function of the interior. The reference or working plane is a fictitious horizontal plane at the table top level or at the floor level, depending on room usage. It may be any other plane as well, for example the vertical plane of a wall at an exhibition.
Fig. 4.6 Direct and indirect illuminance on the working plane.

The illuminance of the reference plane may be characterised by:

- the distribution of illuminance along the plane or
- the distribution of the average values of illuminance along a given direction, or along a typical plane, such as a cross-section
- the average value and uniformity ratio of illuminance on the reference plane.

It is visually interesting to characterise illuminance with its distribution along a vertical plane perpendicular to the window (eg Fig. 5.3). This will be valid only at a given point in time, but if average values are used for such representation, we can obtain sufficient information to study most of the practical problems.

The simplest method of quantifying illuminance is to specify its average values and its uniformity ratio. This can be used for both setting and meeting most practical requirements.

Illuminance at a point of a surface of the interior (E_d) is proportionate to the simultaneous external illuminance at the same place measured on an unobstructed horizontal surface (E_e), which gives the *daylight factor* (DF) in percentage terms:

\[ DF = \frac{E_d}{E_e} \times 100 \]

or

\[ E_d = \frac{DF}{100} \times E_e \]
As external illuminance keeps changing, \( E(t) \) internal illuminance must follow, so its value at time \( t \) will be

\[
E_i(t) = \frac{DF}{100} \cdot E(t)
\]

In this equation the term \( E(t) \) represents the sky as a luminaire which produces that horizontal illuminance, and the term \( \frac{DF}{100} \) is the function of architectural design.
The daylight factor (DF) is an expression of the efficiency of utilising skylight for providing horizontal illuminance in an interior. The daylight factor shows how far the building and its interior (walls, ceiling and the opening structure) as well as external obstructions restrict the potentially available illuminance. The DF would be 100% in the absence of a building and any obstruction.

![Figure 5.3 The relationship of illuminance and daylight factor.](image)

Daylight factor quantifies all the effects of the interior and the exterior on the illuminance of a given internal point. The daylight factor is a function of:
- the position of the point considered,
- the dimensions of the interior,
- the reflectances of interior surfaces,
- the location, size and structure of the opening,
- the location, size and the reflectance of external obstructions,
- the reflectance of the ground.

At a given point in time, or in an unchanging external environment ($E_\text{e} = \text{constant}$), the daylight factor changes from one point to another as the illuminance of the interior changes, i.e., the daylight factor changes according to the distribution of the illuminance of the interior. This means, that a given distribution curve of illuminance $E_\text{e} \ (\text{lx})$ is the same as the curve of daylight factor $DF \ (%)$, possibly with a different scale.

Consequently, the daylight factor can have the following critical values:
- $DF\_\text{av}$ average value,
- $DF\_\text{min}$ minimum value,
- $DF\_\text{min}/DF\_\text{av} = \Psi$, the uniformity ratio

which are in direct ratio to the respective values of illuminance.

The daylight factor quantifies natural illumination in an indirect way, its unit being % and not lux. Although the value of the daylight factor is constant only over a limited range of overcast conditions, it may be used as a first approximation and it is a very useful concept for quantifying daylighting of the interior.

Illuminance at a given point of the interior may have an endless number of values throughout a year, but none of them can characterise natural illumination alone. However, every value of $E_i$ may be connected either
to an $E_0$ or to a period of time, and these two values together give some characterisation, so the following relationships exist:

- $E_1$ is the illuminance of a given point if $E_0$ is the external illuminance,
- the illuminance of a given point is equal to or greater than $E_1$ if the external illuminance equals at least $E_0$,
- the illuminance at a given point is at least $E_1$ for the period of time during a day or during the year when external illuminance is greater than $E_0$.

Thus, a value of illuminance of the interior provides some useful information about natural lighting only in conjunction with another datum: the external illuminance, or the length of time.

Natural lighting may be characterised in two ways:

Directly, by illuminance, $E_1$:
- its distribution along the work-plane or
- its distribution along the sectional plane or
- its average value and uniformity ratio on the reference plane.

Indirectly, the daylight factor, DF:
- its distribution along the work-plane or
- its distribution along the sectional plane or
- its average value and uniformity ratio on the reference plane.

The direct characterisation relates to a given $E_0$ value or to a specified time point or duration. The indirect characterisation is useful to illustrate the spatial character of daylighting interiors, as its relative values do not change.

5.3 Uniformity in space

The uniformity of lighting in space can be quantified by the inequality of illuminance on the working plane. Illuminance at given points of the interior has two components, direct illuminance coming from the external environment and indirect illuminance reflected from the surfaces of the interior. Although, the ratio of direct and indirect components on the working plane changes from one point to another depending on the lighting system, and the two components of illuminance may be nearly equal, still the character of the distribution of illuminance is essentially determined by the direct component.

Direct illuminance at a point on the work-plane mainly depends on the portion of the sky 'visible' from that point and on the average angle of incidence of skylight at the point. Illuminances are proportionate to the size of the 'visible' sky and the cosines of the angle of incidence of light. The size of the 'visible' sky and the angle of incidence of light both depend on where the opening is located in the envelope of the room, so direct illumination depends on the daylighting system.

The spatial variations of daylight can be characterised by:
- the distribution of daylight factor (DF) along the typical direction or
- the average value of the daylight factor $DF_{av}$ and the ratio of $DF_{min}/DF_{av}$ on the reference plane.
Fig. 5.5 The relationship of uniformity and the system of daylighting

In side lighting, the points of the work plane are illuminated by decreasing portions of the sky at increasing angles of incidence as we move away from the window. The distribution of illuminance changes accordingly. In side lighting the illuminance necessarily shows a great lack of uniformity.

The dimensions of the interior, mainly its height, limits the degree to which the variation of illuminance of side lighting can be influenced by the location and size of the window. The architectural parameters affecting natural illumination in side lighting are the following (in decreasing order of importance):

- the depth of the room,
- the size of the window,
- the height of the room,
- the reflectance of the walls,
- the width of the window and
- the reflectance of the ceiling.
It may be instructive to examine the effect of window size and position on the distribution of illuminance (see Figs. 5.6 to 5.9).

Fig. 5.6 The effect of window position on illuminance distribution

The effect of the part of the window which is below the work-plane is negligible from the point of view of illuminating the plane, as light through that part of the window is reduced by multiple reflections and is obstructed by furniture. The part of the window near the ceiling provides illumination mainly for the rear part of the room, while the part of the window with its sill at work-plane level illuminates the area near the window.

A window placed high in the wall illuminates the space more uniformly than a window placed low. A strip window provides more uniform illumination across the room (parallel to the window) than a divided window. This effect diminishes as we move away from the window and it becomes negligible at the back wall.

In top lighting the number of toplights, the height of the space and the design of the toplight determine how uniformly the space is illuminated.

With toplights of equal area and identical structure, the more toplights, the more uniform the illuminance.

With toplights of identical number, structure and arrangement, the higher the interior, the more uniform the illuminance.

The design of toplights determines light distribution, which in turn governs the uniformity of illuminance.

Top lighting can meet any practical requirement of uniform illuminance.
Fig. 5.8 The effect of placement of toplights on illuminance distribution

In combined lighting, the uniformity of illuminance is determined by the joint effect of side lighting and top lighting. The illuminance thus created is the sum of illuminances by the side lighting and the top lighting.

Fig. 5.9 Addition of illuminances in combined lighting.

Combined lighting can meet any practical requirement of uniform illuminance.

5.4 Permanency in time

Daylight illumination necessarily keeps changing as a result of the continuous changing of the sun's position in the sky and of sky conditions. The illuminance of the interior is always proportionate to the illuminance produced by skylight ($E_s$) and by sunlight ($E_b$) if either the interior or an external surface is sunlit.
The changes of natural lighting over time may be investigated in two respects: daily changes or changes over an annual period. Daily changes in the illuminance of a given point of the interior may be found if the daily changes of diffuse skylight (E_d) and direct sunlight (E_s) illuminances are known. Both changes may be characterised by the expected daily values and the cumulative values over the 365 days of the year (i.e., the values exceeded on the indicated number of days).

Illuminance at a point of the interior on a given day of the year changes in direct ratio to a curve which is between the curves of the daily change of E_d(t) and E_d(t) + E_s(t) for the same day.

Disregarding the usually undesirable and unreliable effect of sunlight, changes in the illuminance of the interior follow the changes of external illuminance E_d(t) and its variation corresponds to the variations of sunlight. The entry of sunlight increases this variation.

Daily changes in the illuminance of the interior may be found from the typical distribution curve of the daylight factor and that of the expected daily change of E(t).

During a given day, the expected values of illuminance of the interior are between 0 and E_p(max). There is a different curve of E_i for each value of E_p. At time t*, when the expected value of external illuminance is E_p*, the distribution of illuminance corresponds to the E_i* curve. The illuminance of point P changes between 0 and E_p(max) during the day, and its value is E_p* at time t*.

Practical questions of daylighting more often relate to its yearly change, which refers to the illuminance of the interior and to the expected length of time, namely:
- how large will illuminance be during a given period of the year or
- for which periods of the year can a given value of illuminance of the interior be expected.

These questions may refer to single points of the interior, or to the average of illuminance or to the typical distribution of illuminance. These questions may be answered with the help of the typical distribution curve of the daylight factor DF and of the duration curve of external illuminance E_d(t) (see Fig. 5.12).

At point P, where the value of the daylight factor is DF_p:
- the value of illuminance is at least E_i = (DF_p/100) * E_d**, for T** length of time in the year
- E_i*** illuminance may be expected for T*** length of time in the year, as (100/DF_p) * E_i = E_d***

The connection between illuminance and length of time is similar in average illuminance and in typical distribution.

When investigating the changes of illuminance over time in this way, we must keep in mind that the changes of natural light follow the laws of meteorological-statistics. According to these laws the characteristics of diffuse skylight E_d(t) and E_d(t) and of sunlight E_s(t) are average values of several years, to be expected with a probability of 50%. However, if so desired, values with any other probability can be calculated if the frequency distribution information is available.
5.5 Glare

Glare is the most important problem of visual comfort and of the quality of illumination. Glare is a condition of vision in which discomfort is experienced or visual recognition is reduced. In an extreme case, visual recognition in the field of view is seriously (perhaps completely) impaired. This latter case of 'disability glare' is described as 'blinding'.

Glare is caused by excessive luminance contrast (some high luminance area) in the field of view. In direct glare discomfort is caused by the visible sun or sky, in indirect glare discomfort results from the image of the sun or sky reflected from a shiny surface in the field of view.

The higher the luminance, and the greater the visible size of its surface, the greater the risk of glare. The nearer the surface of high luminance to the direction of view, the greater the glare problem. A higher background luminance (thus the reduced contrast), reduces the glare.
In natural lighting, glare may be caused by the sun, the sky or a sunlit and reflective outdoor surface visible from the interior, or by the sunlight entering the interior. It is difficult (and often impossible) to control the luminance of these surfaces. Glare has to be taken into account as an undesirable effect occurring with some probability, the main features of which are the following:

- the degree of glare keeps changing during the year in all cases,
- not even the most disadvantageous form of daylighting causes glare all the time,
- there are forms of daylighting that provide glareless illumination.

The probability of glare from the sun, the sky and external obstructions mainly depends on where the opening is in the field of view, i.e., on the lighting system. Generally the better the visual connection between the exterior and the interior, the greater the risk of direct glare.

In side lighting, the exterior seen through the window is near the middle of the field of view, and this is why the probability and degree of expected glare is high. Of course, the risk of glare in these cases also depends on the orientation of the opening.

In top lighting, the visible part of the sky is above the normal field of view, so the probability and degree of direct glare is low.

Indirect glare caused by the penetration of beam sunlight into the interior depends less on the daylighting system.

5.6 Direction of light and the effect of shadows

At a given point in the space, the different illuminances of surfaces facing different directions result in shadows. Shadows help us recognise the spatial arrangement of objects and the three-dimensional quality of surfaces. Shadowless ('washed out') lighting and lighting with very hard shadows are equally undesirable.

Hard shadows are especially uncomfortable if they reduce the visibility of surfaces that should be seen. The shadow effect may be characterised with the help of the ratio of vertical and horizontal illuminance (or the vector/scalar ratio; see note on p. 48).

The shadow effect of natural lighting primarily depends on the lighting system, and secondarily on reflection from interior surfaces. In side lighting, the shadow effect is necessarily great, as lighting is highly directional. This is practically impossible to change, therefore the problem of shadows can only be solved by admitting light from several directions.

In top lighting and combined lighting, the shadow effect may be adequately influenced by choosing the location of the openings.

5.7 Colour appearance

Good colour appearance is a result of harmony between illuminance and the quality of light characterised by the colour temperature and colour composition of the light. The illumination of the environment is found pleasant, if low values of illuminance are provided by 'warm' light, and high values of illuminance by 'cool' light.
This harmony exists naturally in the exterior, since this demand originates from human conditioning in the natural environment. However, illuminance in the interior is much lower, only one tenth to one hundredth of external illuminance. Consequently, this harmony does not exist automatically in the interior.

The smaller the average daylight factor of the interior, the higher the probability of unpleasant colour appearance at least in part of the year. Taking into account the most probable values of the colour temperature of natural light, natural illumination is expected to meet this demand for the best part of the year.

5.8 Colour rendering

Human vision developed under natural light, so the ‘natural colours’ of surfaces and materials are those seen under natural light. The colour rendering of daylighting in the interior is excellent, unless the colour of glazing or coloured surfaces of the interior distort the quality of light.

6 DAYLIGHTING DESIGN

Designing natural lighting for the interior means designing the interior architecturally in a way that it meets illumination requirements. These requirements are concerned with:

- average illuminance and uniformity,
- the degree of acceptable glare,
- shadows and the direction of light,
- colour appearance and
- colour rendering.

Of these, the requirement of illuminance needs quantitative designing, the others can be met usually by qualitative treatment, by the suitable formation of certain details of the interior.

6.1 Designing illuminance

Most countries have standards or codes of practice for the values of required average illuminance \( E_{R} \) and for uniformity of artificial lighting in space \( (\psi) \) for different activities and areas. It is advisable to design the natural illumination of the interior on the basis of these standard values. Thus, daylighting is designed on the basis of the required average illuminance \( E_{R} \) and uniformity \( \psi \).

As the illuminance of the interior changes continuously

- if \( E_{R} \) is smaller than the greatest average illuminance during the year, the natural illuminance of the interior can be said to be suitable for part of the year, when external conditions exceed a given value,
- if \( E_{R} \) exceeds the greatest average illuminance during the year, the natural illuminance of the interior does not meet requirements all the year round.

It depends on the architectural form of the interior and on the (given or designed) exterior under what external conditions and for what length of time of the year there will be adequate amounts of natural light, or indeed if such external conditions are to be expected at all.
In designing natural lighting, it should be decided:
• under what external conditions or
• for what length of time during the working hours of the year daylight illuminance will suffice.

The external conditions and length of time in the year are interconnected as shown by the daylight availability curve (eg Fig.5.12).

When defining external conditions, the condition of the sky and the illuminance \( E_0 \) should be determined. This value of \( E_0 \) and condition of the sky is referred to as the design sky.

In the course of the above it must be decided which of the three, precisely definable conditions of sky (overcast, foggy or clear) is most typical at the given geographical location.

The design sky is generally described in terms of the design external illuminance \( E_{eD} \), which can be defined by the percentage of days of the year when the illuminance requirements are to be met by natural lighting. It is often suggested to choose a value of \( E_{eD} \) which makes it possible to satisfy illuminance requirements by natural lighting in some 90% of the days (of working hours) of the year.

Greater values of \( E_{eD} \) result in smaller openings and vice versa.

The illuminance and sky condition for design vary for different countries or regions and the value of \( E_{eD} \) is usually established by local standards. If the number of sunshine hours is less than 2500 h/year, the preferred strategy is:
• the design sky condition is taken as overcast sky and
• the value of \( E_{eD} \) is between 5 000 and 10 000 lx.

Effective design is based on the required daylight factor \( D_F \), which may be determined by the values of \( E_R \) and \( E_{eD} \) as follows

\[
D_F = \frac{E_R}{E_{eD}} \times 100 \quad (\%)
\]

Natural lighting for a required illuminance is designed on the basis of the daylight factor.

The task of designing in practice is the following:

Given is an interior space with known geometry and dimensions, the material and colour of its surfaces have been chosen, and the external environment is known.

The function of the room is known.

Taking into account the architectural concept and practical possibilities, the architect makes decisions on
• the lighting system: whether to use side-, top- or combined lighting,
• the form and type of lights (openings).

This is followed by the actual process of designing. In the course of this, the main parameters, the number and the arrangement of the chosen type of light must be decided.
Designing for daylighting is indirect as its aim is to achieve the DF$_R$, the required daylight factor. The task is to design an interior with as many and such lights (openings), that the desired daylight factor be achieved with the given external environment and conditions. If the daylight factor of the interior is DF$_R$, the illuminance is equal to or greater than $E_R$ when external illuminance is equal to or greater than $E_{ed}$.

The design of daylighting is different in side or top lighting.

In side lighting, the requirements of achieving a certain average illuminance and uniformity usually cannot be met. Illumination necessarily lacks uniformity and it is rapidly reducing with distance from the window. Therefore, the requirement is set for a certain point, 'M' of the working plane, and its value must be exceeded between that point and the window (the assumption is that the rear of the room beyond 'M' can be used for visually less exacting tasks or storage).

![Diagram of daylight factor with side lighting](image)

**Fig.6.1 Required daylight factor with side lighting.**

If the required average illuminance for a given activity is $E_R$, and the allowable uniformity ratio is $\psi$, then the minimum acceptable illuminance is $\psi \times E_R$ so the required daylight factor at point 'M' is:

$$DF_{R_{(min)}} = \frac{\psi \times E_R}{E_{ed}} \times 100$$

(%)\n
In top- or combined lighting, the requirements of average illuminance and uniformity can both be met, therefore in these systems, design is based on the average value of the daylight factor according to the following equation:

$$DF_R = \frac{E_R}{E_{ed}} \times 100$$

(%)\n
Daylighting for illuminance may be designed by:

- graphic methods,
- mathematical calculations and
- physical modelling.
Fig. 6.2 Required daylight factor at top lighting.

Reference back to Fig. 2.14 shows that a point of the work plane can receive light from the sky (and sun) three ways:
a) directly, from the portion of sky visible from that point
b) reflected by the surface of an external object
c) by light which enters through the window, but reaches the point considered only after one or more internal reflections.

The illuminance of the point \( E \) is the sum of these three components and the daylight factor (as defined on p.35) is the sum of three corresponding components:

\[
DF = SC + ERC + IRC
\]

where
- \( SC \) = sky component
- \( ERC \) = externally reflected component
- \( IRC \) = internally reflected component.

There are numerous methods available for the determination of each or all these components. These graphic or mathematical methods vary greatly in their reliability and accuracy. Many of them neglect important factors and make considerable and debatable simplifications. Most of them (graphic methods) provide the result for a given (or assumed) opening, so the design will have to be a series of trial-and-error steps. All methods calculate the lighting at one given point of the work plane (or reference plane). If one is interested in the distribution of daylight, the calculation must be repeated for a large number of points, then the daylight contours can be interpolated.

The better known graphic methods are
- the Grün method
- the Waldram method
- the pepper-pot diagram
- the Daniuk method
- the BRS method.

The better known mathematical calculations are
- CIE nomograms
- the total flux (or lumen) method, using tables of utilisation factors
- the efficiency method
- the generative method.
Many widely used computer programs are generally suitable for interiors of simple geometry. More complicated interiors or fenestration require more advanced programs, which need longer time and more expertise.

The natural lighting of interiors can be investigated most reliably by model measurements in an artificial sky. Fig 6.3 shows the three generic types of artificial skies. Each has some advantage and each can give satisfactory results. The more up-to-date ones can simulate different sky luminance distributions by switching. Interiors of any geometry, surfaces of any quality, any structure or form of opening can be examined by model studies. The accuracy of this method meets all practical requirements. Indeed, most daylighting design methods have been developed on the basis of model studies in artificial skies.

6.2 Limiting glare

If glare is to be avoided or restricted in daylighting, the following circumstances have to be taken into account:
- Glare would occur only in part of the time of use, and the degree of glare would change during this time.
- Direct glare is caused by sunlight penetration.
- The risk (probability) of glare is greater in side- and combined lighting than in top lighting.
- Although glare has to be restricted in most cases, there are interiors without such a requirement.

If glare has to be avoided, the problem may be solved in most cases with the help of some architectural device, usually attached to the opening, completing or modifying it. Most effective are the responsive devices, with features changed automatically, either by moving...
components or by changing their transparency. Other, common glare protection devices can meet the above requirements adequately only part of the time. Non-responsive devices unnecessarily reduce the illumination of the interior. It is very important to remember that perfect solar shading devices do not necessarily provide perfect protection from glare.

The risk of glare can be reduced or even avoided by architectural means, which are aimed at reducing sharp contrasts of luminance within the visual field or contrast grading. Some typical examples are:
- avoid dark coloured window frames or glazing bars which may be seen against a bright outdoor view
- avoid dark colours for surfaces surrounding a window
- for a window in a thick wall the reveals should be tapered (or rounded) to provide contrast grading
- avoid a visual task being placed against a bright background
- sunlight surfaces of shading devices should not be directly visible, or if they are, they should not be of a light (reflective) colour.

6.3 Direction of light and the effect of shadows

In natural lighting, shadows and the direction of light depend predominantly on the lighting system. In side lighting, illumination is highly directional. This undesirable effect may only be reduced to some extent by increasing the reflectance of walls. In cases where there are exacting requirements regarding shadows, side lighting is not the lighting system of choice. In top and combined lighting, demands concerning shadows and the direction of light can be easily met by a suitable arrangement, number and size of openings.

6.4 Colour appearance

Good colour appearance may require changing the quality of natural light from time to time. This is practically impossible, therefore the demand of colour appearance has to be regarded as one which is automatically met most of the time of use, but cannot be ensured at all times. Natural lighting may not be adequate from the point of view of colour matching at some of the time.

The use of transparent surfaces which change the quality of natural light (eg tinted glasses) may increase the number of cases and the length of time when colour appearance is unsatisfactory.

6.5 Good colour rendering

The colour rendering of natural lighting is excellent. This is true also for daylighting the interior, if the surfaces of the interior are only slightly coloured or not at all. In the interest of colour rendering, it is advisable to restrict the ratio of brightly coloured surfaces in the interior.

* A measure of directionality is the vector/scalar (VIS) ratio. Scalar illuminance (E_{sc}) is the mean spherical illuminance, ie a measure (in lux) of light arriving at a point in space from all directions. The illuminance vector has both a magnitude and a direction. The former is the maximum difference in illuminance between two diametrically opposed points of a small sphere. It is denoted ΔE_{max}. If the VIS ratio (ΔE_{max} / E_{sc}) is 0, we have a completely diffuse, omnidirectional light field. VIS = 4 means monodirectional light.

In practice values between 0.2 and 3.5 are encountered. For looking at a human face values between 1.1 and 1.5 are preferred, with a vector altitude of 15°-45°. A problem with side lighting is that at the back of a room the vector is almost horizontal (Fig 6.4)
7 DESIGN METHODS

The two recommended methods will be described first, as the only ones which can be used without the assumption of a solution. The generative method will determine the necessary window size for a required daylight factor, whilst the efficiency method does the same for toplights.

7.1 The generative method

The following method was developed by the author on the basis of artificial sky measurements at the Technical University of Budapest. The method is suitable for calculation of the window area required (SwR) with the following limitations:

- the dimensions of the room are within the following values:
  - width 2.5-15 m,
  - depth 2.5-12 m,
  - height 2.5-5 m;
- if there is an obstruction in front of the window, it can be described approximately by horizontal and vertical lines;
- the structure of the window to be built is known;
- the pollution (degree of dirtiness) of the environment is known.

Starting data: (refer to Figure 7.1.)

1. geometrical data of the room, (width, depth and height)
2. average reflectance of the ceiling,
3. average reflectance of walls of the room, which have no window,
4. vertical and horizontal angles subtended by the obstruction,
5. average reflectance of the obstruction,
6. type and glazing of the window to be used and its location,
7. the environment of the building.
8. the required daylight factor or illuminance

The method step by step:

The fundamental equation of the calculation is

\[
\frac{DF_{R\text{(min)}}}{k_p * k_z * k_o} = DF_s * k_s
\]
1) \( DF_{R(\text{min})} \) is the required daylight factor. Its value is obtained either from a standard or code, or from the required (standard) illuminance for the activity in the room, using the following equation:

\[
DF_{R(\text{min})} = \Psi \times \left[ \frac{E_r}{E_{\text{ed}}} \right] \times 100 \ [\%] \quad \text{(refer to p.45)}
\]

2) \( k_n \) is a correction factor for internal reflectances (from Fig.7.2)

3) \( k_w \) is a correction factor for the window's structure. Its value can be calculated from the following equation:

\[
k_w = \tau_g \times \tau_f \times \tau_d
\]

ie the product of glazing, frame and dirt coefficients, the values of which may be taken from following table:

<table>
<thead>
<tr>
<th>Glazing</th>
<th>( \tau_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat glass, single pane</td>
<td>0.9</td>
</tr>
<tr>
<td>flat glass, double pane</td>
<td>0.8</td>
</tr>
<tr>
<td>textured, diffusing reinforced glass</td>
<td>0.6</td>
</tr>
<tr>
<td>glass blocks mounted in concrete</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frame</th>
<th>( \tau_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>metal frame, single</td>
<td>0.8</td>
</tr>
<tr>
<td>metal frame, double</td>
<td>0.65</td>
</tr>
<tr>
<td>wooden frame, single</td>
<td>0.75</td>
</tr>
<tr>
<td>wooden frame, double</td>
<td>0.5</td>
</tr>
<tr>
<td>composite window (Teschauer)</td>
<td>0.8</td>
</tr>
<tr>
<td>reinforced concrete window</td>
<td>0.6</td>
</tr>
<tr>
<td>glass-concrete opening</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect of Dirt / Cleaning</th>
<th>( \tau_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-urban, suburban/regular cleaning</td>
<td>0.9</td>
</tr>
<tr>
<td>non-urban, suburban/occasional cleaning</td>
<td>0.7</td>
</tr>
<tr>
<td>residential area/regular cleaning</td>
<td>0.8</td>
</tr>
<tr>
<td>residential area/occasional cleaning</td>
<td>0.6</td>
</tr>
<tr>
<td>industrial area/regular cleaning</td>
<td>0.7</td>
</tr>
<tr>
<td>industrial area/occasional cleaning</td>
<td>0.5</td>
</tr>
<tr>
<td>it clean state</td>
<td>1</td>
</tr>
</tbody>
</table>
4) $k_o$ is a correction factor for the obstruction. Its value can be calculated from the following equation:

$$k_o = 1 - c(k_e (k_{e1} - k_{e0}))$$

$c$ obtained from Fig. 7.3 (based on $p_0$ - see also Fig. 7.1)

$k_e$ obtained from Fig. 7.4 (based on $\varepsilon$ and $h$ - see Fig. 7.1)

$k_{e1}$ and $k_{e0}$ from Fig. 7.5 (based on $\gamma$ and $\alpha$ - see Fig. 7.1)

![Graph showing values of $c$](image)

Fig. 7.3 Values of $c$

5) The left side of the main equation can be calculated based on determined values of $DF_{R_{(Min)}}$, $k_f$, $k_{t}$ and $k_0$.

6) The right-hand side of the main equation: $DF_o k_o$ (an initial value for $DF$ and correction term for window position) as a function of relative window area ($A$) can be determined as follows:

On the basis of the height of the room ($h$), a group of diagrams has to be chosen from Fig. 7.6.1...7.6.5

The appropriate ones are:

- If $2.5 \leq h < 3$ m Fig. 7.6.1
- If $3 \leq h < 3.5$ m Fig. 7.6.2
- If $3.5 \leq h < 4$ m Fig. 7.6.3
- If $4 \leq h < 4.5$ m Fig. 7.6.4
- If $4.5 \leq h < 5$ m Fig. 7.6.5

The aim is to plot the curve that shows how the $DF$ depends on the area of window in a room of given dimensions and the location of the window i.e. $DF_o k_o = f(A)$ function.

These values of pairs of $DF_0 - k_0$ can be determined from the selected Figure. (7.6.1...7.6.5) according to the diagram given in Fig. 7.6 (the top part of each graph gives the $DF_0$ and the lower part the $k_0$ factor).

51
Fig. 7.4 The values of $k_e$ for different room heights.
Values of $k_y$ for different room widths (a)

Fig. 7.5 The values of $k_y$, for different room widths (a)

On the following three pages:

For the top part of each graph the axes are

vertical: daylight factor
horizontal: room depth, $b$

and the curves represent different room widths, $a$

The lower part of each graph gives the $k_y$ coefficient for the right-hand side of the fundamental equation. The three curves of this lower graph are for three window positions: 'upper', if the window head is at or near ceiling level, 'lower' if the window sill is at work-plane level and 'middle', an intermediate position. Note that for the largest window size there is only one curve as it is both 'upper' and 'lower'.

Four graphs of each Fig. are for different relative (%) window areas.

Maximum area of window is $(h-0.85)\cdot a$, as the height of the working plane is generally 0.85 m, the maximum relative area is $A_r$. 

53
Fig. 7.6 Determination of DF₀₁ & kₐ₁ to DF₀₄ & kₐ₄ or how to read Figs. 7.6.1 to 7.6.5

Fig. 7.6.1 DF₀ and k₀ if 2.5 \( \leq h < 3 \) m
Fig. 7.6.2 \( D_F \) and \( k_a \) if \( 3 \leq h < 3.5 \) m

Fig. 7.6.3 \( D_F \) and \( k_a \) if \( 3.5 \leq h < 4 \) m
Fig. 7.6.4 $DF_o$ and $k_a$ if $4 < h < 4.5$ m

Fig. 7.6.5 $DF_o$ and $k_a$ if $4.5 < h < 5$ m
7) With the above pairs of values the $DF_{0}k_{a} = f(A)$ curve can be drawn as follows:

![图](https://example.com/figure77.png)

Fig. 7.7 Construction of the $DF_{0}k_{a} = f(A)$ curve.

8) The last step is the determination of required area of the window for the given room:

On the basis of the calculated value of the left side of the main equation

$$\frac{DF_{R_{(min)}}}{k_{p}k_{r}k_{o}}$$

and the $DF_{0}k_{a} = f(A)$ curve,

![图](https://example.com/figure78.png)

Fig. 7.8 Determination of relative area of window $A_{wR}$.

The points of intersection give the required relative window size $A_{wR}$ in %.

9) Finally the required area of window is the product of the wall area and the relative window area:

$$S_{wR} = \frac{A_{wp}h\alpha}{100}$$
EXAMPLE
The following example illustrates the use of the method.

Starting data:
1. \(a = 14 \text{ m}, \quad b = 6 \text{ m}, \quad h = 4.1 \text{ m}\)
2. \(r_W = 55\%\)
3. \(r_C = 65\%\)
4. \(\varepsilon = 24^\circ, \quad \gamma_1 = 25^\circ, \quad \gamma_2 = 0^\circ\) (obstruction angles, Fig. 7.1)
5. \(p_0 = 15\%\)
6. Structure of window: metal frame, double flat glass, upper;
7. Environment: residential area/occasional cleaning;
8. \(DF_{R_{(min)}} = 1\%\)

Calculation:
1) \(DF_R = 1\%\)
2) \(k_f = 0.58\) (see Fig. 7.2)
3) \(\tau_0 = 0.8, \quad \tau_f = 0.65, \quad \tau_d = 0.6\) (see p.52)
4) \(C = 0.92\) (see Fig. 7.3)
5) \(k_f = 0.58\) (see Fig. 7.4)
6) \(k_{\gamma_1} = 0.6, \quad k_{\gamma_2} = 0\) (see Fig. 7.5)
7) \(k_0 = 1 - 0.92 \times (0.58 \times (0.6 - 0)) = 0.68\)
8) \(DF_{R_{(min)}} / k_p \times k_f \times k_d = 1 / (0.58 \times 0.31 \times 0.68) = 8.2\%\)
9) \(DF_1 \times k_{\alpha_1} = 11.9 \times 1 = 11.9\% \quad A_1 = 79\%\) (see Fig. 7.6.4)
10) \(DF_2 \times k_{\alpha_2} = 9 \times 1.1 = 9.9\% \quad A_2 = 59\%\)
11) \(DF_3 \times k_{\alpha_3} = 6 \times 1.1 = 6.6\% \quad A_3 = 40\%\)
12) \(DF_4 \times k_{\alpha_4} = 2.8 \times 1.2 = 3.4\% \quad A_4 = 20\%\)

9) The required area of window is:
\[S_{WR} = \frac{(A_{WR} \times h \times a)}{100} = \frac{(49 \times 4.1 \times 14)}{100} = 28.1 \text{ m}^2\]

7.2 The efficiency method

The following method is suitable to determine the required area of a toplight if it enjoys the effect of the whole sky (i.e., it 'sees' the whole sky). So, of the toplight types discussed earlier, it can be used for the horizontal-, pitched-, dome and pyramid types.
Starting data: (refer to Fig. 7.9.)

1. dimensional data of the room (width a, depth b and height h)
2. height of work-plane above the floor r
3. average reflectance of the room's ceiling $p_c$, walls $p_w$ and floor $p_f$
4. type and glazing of the toplight
5. internal dimensions (p, q, m) and reflectance of toplight (Fig. 7.10)
6. pollution (dirtiness) of the building's environment
7. the required daylight factor $DF_R$ or illuminance $E_R$

---

The method step by step:

The fundamental equation to calculate the required area of a toplight is

$$S_{TR} = \frac{DF_R \cdot a \cdot b}{100 \cdot \tau_a \cdot \tau_s \cdot \tau_d \cdot k \cdot \eta} \quad (m^2)$$

1) $DF_R$ is the required daylight factor. Its value is obtained either from a standard or code or from the required (standard) illuminance for the activity in the room using the following equation

$$DF_R = \left( \frac{E_R}{E_{eD}} \right) \cdot 100 \quad [%]$$

(refer to p.45)

---

Fig. 7.9 Symbols used for the room.

Fig. 7.10 Symbols used for a toplight.
2) $\tau_g$ is the transmittance of the transparent part of the toplight

<table>
<thead>
<tr>
<th>Type of glazing</th>
<th>$\tau_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat glass, single layer</td>
<td>0.9</td>
</tr>
<tr>
<td>flat glass, double layer</td>
<td>0.8</td>
</tr>
<tr>
<td>wired glass, single layer</td>
<td>0.77</td>
</tr>
<tr>
<td>wired glass, double layer</td>
<td>0.63</td>
</tr>
<tr>
<td>plastic</td>
<td>0.8</td>
</tr>
</tbody>
</table>

3) $\tau_s$ is the coefficient of obstruction by the structure

<table>
<thead>
<tr>
<th>Structure</th>
<th>$\tau_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>self supporting without structure</td>
<td>1</td>
</tr>
<tr>
<td>metal structure</td>
<td>0.9</td>
</tr>
<tr>
<td>wooden structure</td>
<td>0.8</td>
</tr>
<tr>
<td>reinforced concrete structure</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4) $\tau_d$ is the coefficient of reduction by dirt

<table>
<thead>
<tr>
<th>Effect of Dirt / Cleaning</th>
<th>$\tau_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-urban or suburban/regular cleaning</td>
<td>0.8</td>
</tr>
<tr>
<td>non-urban or suburban/occasional clean</td>
<td>0.55</td>
</tr>
<tr>
<td>residential area/regular cleaning</td>
<td>0.7</td>
</tr>
<tr>
<td>residential area/occasional cleaning</td>
<td>0.4</td>
</tr>
<tr>
<td>industrial area/regular cleaning</td>
<td>0.55</td>
</tr>
<tr>
<td>industrial area/occasional cleaning</td>
<td>0.25</td>
</tr>
<tr>
<td>in clean state</td>
<td>1</td>
</tr>
</tbody>
</table>

5) $k_w$ is the well efficiency, its value can be determined from the well's (geometrical) index ($i$) and the reflectance of its internal surfaces ($p_{tw}$)

Well index: $i = \frac{m^* (p + q)}{2 + p^* q}$

$k_w$ can be found from the following graph:

Fig. 7.11 Efficiency of the well: $k_w$
6) \( \eta \) is the room efficiency, which can be obtained from the following table on the basis of the room index \( RI \), the average reflectance of ceiling \( \rho_C \), walls \( \rho_W \) and floor \( \rho_F \). The room index \( RI \) can be calculated from the main room dimensions

\[ RI = \frac{a*b}{(a+b)*(h-r)} \]

<table>
<thead>
<tr>
<th>RI</th>
<th>0.3</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_C )</td>
<td>0.8</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>( \rho_W )</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>( \rho_F )</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

6) These values substituted into the main equation give the required area of toplight.

**EXAMPLE**

The following example illustrates the use of the method.

Starting data:

1. \( a = 16 \text{ m} \)  \( b = 8 \text{ m} \)  \( h = 6.2 \text{ m} \)
2. \( l = 0.85 \text{ m} \)
3. \( \rho_W = 50\% \)  \( \rho_C = 80\% \)  \( \rho_F = 30\% \)
4. type of toplight: self supporting dome with plastic glazing
5. \( p = 1.2 \text{ m} \)  \( q = 1.2 \text{ m} \)  \( m = 0.6 \text{ m} \)  \( \rho_{HW} = 80\% \)
6. Environment: non-urban, with regular cleaning
7. \( E_R = 200 \text{ lx} \) let the 'design sky' be: \( E_{RD} = 5000 \text{ lx} \)

1) \( DF_R = (200/5000) \times 100 = 4\% \)
2) \( \tau_g = 0.8 \)
3) \( \tau_s = 1 \)
4) \( \tau_d = 0.8 \)
5) \( i = 0.6 \times (1.2+1.2) / 2 \times 1.2 \times 1.2 = 0.5 \)
\( \alpha = \rho_{HW} = 80\% \)
\( k_w = 0.77 \)

6) \( RI = (16 \times 8) / ((16+8) \times (6.2-0.85)) = 1 \)
\( \alpha = \rho_W = 50\% \)  \( \rho_C = 80\% \)  \( \rho_F = 30\% \)
\( \eta = 0.62 \)

7) \( S_{TR} = [(4/100) \times (16 \times 8)] / (0.8 \times 0.8 \times 0.77 \times 0.62) = 16.7 \text{ m}^2 \)
as the area of one unit of toplight is \( 1.2 \times 1.2 = 1.44 \text{ m}^2 \), the required number of toplights is \( 16.7 / 1.44 \approx 12 \)
7.3 Mathematical methods

The above two, as well as other mathematical methods do not separate out the three components of the daylight factor. These all rely on equations, graphs and diagrams and data tables. Most would produce the necessary aperture area for the required daylight factor as a function of an assumed arrangement and structure of openings and data relating to both the interior and the environment.

7.3.1 Total flux (lumen-) method

This method gained wide popularity in the USA, but elsewhere only its toplighting version gained some acceptance. First the illuminance of the window plane must be established. Multiplied by the window area and transmittance this gives the total luminous flux entering the room. Extensive tables will then give values of the coefficient of utilisation (CU) for the illuminance at three 'station points' (SP) along the window centreline: max, mid and min, as a function of room dimensions and wall reflectances.

7.3.2 CIE nomograms

Sets of these nomograms are available for different types of toplights, such as sawtooths and monitors. The sky is optional but no obstructions can be allowed for. The work-plane level is given. The nomograms will give the toplight area as a function of ratios of internal dimensions and the required average illuminance. Only the main features of toplights are taken into account.

7.4 Graphic methods

In this section the Grün method, the Waldram diagram, the 'pepper-pot' diagram and the Daniluk method will be described briefly and the BRS method will be given a more detailed introduction.

7.4.1 The Grün method

This method can determine the sky component only. It is similar to the British sky factor method (the predecessor of the BRS method) except that this uses a geometrical construction instead of a protractor for the initial sky component. It still relies on a protractor for the correction factor. The opening must be rectangular, but the reference plane is optional. The results are valid for an unglazed aperture, otherwise they should be multiplied by the transmittance of the glazing.

Using a section of the room considered, a semicircle of a radius of 50 units (eg 50 mm) is drawn from the P point considered, to represent the sky (Fig.7.13). Limiting lines are drawn from P to the sky through the corner point of the window head and of the sill. (The average altitude angle of these two lines must also be found.) Intersections with the semicircle are projected vertically down to the base line. The horizontal distance along the base line between the two intersection points in mm (or the units used for the radius) gives the value of the initial sky component (SCo). This would be valid for an infinitely long window. For windows of finite length two correction factors (c', c'') must be found from the plan of the room, using the protractor provided (Fig.7.12).
The fundamental equation is:

\[ SC_F = SC_{up} \cdot (c' + c'') \]

**EXAMPLES**

The method is illustrated by some examples:

1) Fig 7.12 shows a room in plan and section, with a window (C) and a toplight (D). The geometrical construction shown in Fig.7.13 produces the following initial values:

- \( SC_{cD} = 6.2 \)
- \( SC_{cD} = 7.5 \)
- \( \delta_C = 19° \)
- \( \delta_D = 64° \)

The dotted line on plan shows the extent of the toplight. Note how the centreline of this is projected down onto the work plane and the plan.

From the plan the angles \( \alpha_C, \beta_C, \alpha_D \) and \( \beta_D \) are transferred to the protractor (in practice a transparent copy of the protractor can be used as an overlay). Semicircles for the 19° and 64° average altitude angles are drawn in (or at least visualized) by interpolation. Where the limiting lines intersect this semicircle, the results are read along the 'c' curves:

- \( c'_C = 0.15 \)
- \( c''_C = 0.15 \)
- \( c'_D = 0.11 \)
- \( c''_D = 0.11 \)

Thus the sky components are:

- \( SC_C = 6.2 \cdot (0.15 + 0.15) = 1.86\% \)
- \( SC_D = 7.5 \cdot (0.11 + 0.11) = 1.65\% \)

Although the toplight is only 1/3 of the area of the window, it provides almost as much lighting as the side window.
In side-lighting the daylight factor at the back wall may be 2–4 times larger than this sky component. In top-lighting, the total daylight factor generally is not larger than 1.5 times of the sky component.

This method can be used very easily for comparative evaluation of different apertures. Two examples will illustrate this:

2) Question: What is the difference in daylighting at point P if the window (of the same size) is located with its sill at work-plane level (A) or its head near the ceiling (B)? (The correction factors for width need not be considered, as the window size is the same and the difference in altitude angles is not very large)

The sectional construction shows that the initial sky components are: for A: 4% and for B: 8.5%, thus the alternative B provides more than twice as much light to point P as alternative A.
3) Question: What is the contribution of the two identical toplights to the five points indicated across the cross-section of a factory? What is the pattern of illuminance distribution on the work plane?

As the section is symmetrical, only three points need to be considered: A, B and C, and as the question relates to the pattern (and not absolute quantities) the correction factors need not be considered.
7.4.2 Waldram diagram

This is the best known example of the family of 'equal area diagrams'. It is a cylindrical projection of half the sky hemisphere, where the horizontal (azimuth) scale is linear, but the vertical scale is proportionate to $1 - \cos(2\theta)$, as shown in Fig. 7.14.

If the diagram is (say) 25 cm $\times$ 20 cm = 500 cm$^2$, then each cm$^2$ represents 0.1% of daylight factor sky component (the whole sky is 100%, the half sky 'seen' by a vertical window is 50%).

The window area must be drawn on this diagram, as indicated by Fig. 7.15. The vertical sides are vertical, but the horizontal edges must be drawn along the 'droop-lines', shown in Fig. 7.16. The area of window in cm$^2$ would thus give the sky component (SC). Fig. 7.16 is shown for overcast sky, but similar diagrams are available for clear sky, both for unglazed and glazed openings.

An obstruction can also be drawn in (as in Fig. 7.15) and the area of this, multiplied by the reflectance of that surface, gives the ERC, the externally reflected component.
7.4.3 'Pepper-pot' diagram

This is based on similar principles to the above, but here each 0.1% of sky component is represented by a dot (Fig.7.17). If daylighting at a point P is considered, an interior perspective view of the window must be constructed from that point 'P' as the view-point with a perspective distance (from P to the picture-plane) equal to the radius of the circle at the middle of the diagram (this indicates the 45° view-cone).

A transparent copy of this diagram is then laid over the window, and the number of dots within the window area are counted. 0.1 times this number is the SC, or sky component. Dots falling on the surface of an external obstruction also drawn into the perspective can be counted and multiplied by the reflectance of that obstruction; this gives the ERC.

Fig.7.17 The 'pepper-pot' diagram, for 20 mm perspective distance

7.4.4 The Daniluk method

The sky hemisphere is divided into equal areas (rectangles or triangles) by longitudinal semicircles in one direction and parallel semicircles in the other direction (Fig.7.18). A set of polar diagrams is then produced, which are to be used to measure the area of sky (or of external obstructions) 'seen' through the window from the point considered. Such polar diagrams are available for both uniform and overcast sky. The result gives the SC and ERC.
7.4.5 The BRS method

The method was developed at the British Building Research Station (now called the Building Research Establishment) and gained wide acceptance. It is using 10 protractors, of which one (No.2) is shown in Fig.7.19 below. The odd numbered ones are for uniform sky and the even numbers for overcast sky; both for vertical, horizontal, 30° or 60° sloping glazing or for unglazed apertures.

Side A of the protractor is to be used on section to get the initial sky component (and the average altitude angle) and side B is used on a plan, to get the correction factor for windows of finite length, as shown in Fig.7.20. Note that the latter gives two readings (for N and M). If these two are on either side of the centreline, then the correction factor is the sum of the two. If they are on the same side (i.e., if the point considered (0) is to one side of the window) then the correction factor is the difference of the two readings.

The externally reflected component (ERC) is found taking the obstruction as if it were a part of the sky, but then multiplying the result by the reflectance of that surface.

It is similar to the Grün method described in section 7.4.1, but further refined and it is supplemented by a nomogram for finding the internally reflected component (IRC). It is thus the only generally used graphic method which produces all three components of the daylight factor.
Fig. 7.21 shows the IRC nomogram. Its use involves the following steps:

1. find the window area as well as the total room surface area (including floor, ceiling, walls, windows); calculate their ratio and locate this on scale A.
2. find the average internal reflectance (the small table attached to the nomogram may be used; find the walls-to-total surface ratio, locate it in the first column; find the average value in the column headed by the wall reflectance; interpolate both ways if necessary (it is assumed that the reflectance of the ceiling is 70% and of the floor 15%).
3. locate the average reflectance on scale B and with a straight-edge from A to B find the IRC on scale C; this is the result if there is no external obstruction.
4. If there is an obstruction, locate its altitude angle (taken at the window centreline) on scale D.
5. with a straight-edge from D through the previous result on C find the corrected IRC on scale E.

---

Fig. 7.21 The IRC nomogram of the BRS
The result is taken as constant throughout the room.
8 RECENT DEVELOPMENTS

Daylighting had three basic problems for a long time:

- the undesirable inequality of illuminance with side lighting
- unwanted direct sunlight, which may cause glare
- the fact that only rooms with an external wall or roof can have daylighting.

Much work has been devoted to finding solutions for these problems in recent times and some new devices have been developed to improve the distribution, to improve visual comfort, to utilise direct sunlight and to provide daylight for interior, windowless rooms.

8.1 Light shelves

With side-lighting, ie with ordinary windows the illumination is very large near the window and it is rapidly reducing with distance from the window. In sunny climates some form of shading device is often used, which in turn reduces daylighting. Light shelves provide an ideal solution for these problems. These consist of a horizontal element, with a reflective upper surface, positioned either outside or inside of the window (Fig.8.1), normally at about 2/3 of the window height (at a minimum of 2.1m from the floor). Their purpose is to reflect the light, especially beam sunlight, towards the ceiling, which in turn will diffusely reflect it towards the rear part of the room. They work well if the room height is in the order of 3 m or more.

So, light shelves reduce the light near the window and increase it at the back of the room, thus ensure a better uniformity; they can make use of beam sunlight without the risk of glare. The externally fitted light shelf can also serve as a shading device for the lower part of the window.

Many varieties of light shelves exist. Some have a specular top surface, some are diffusing and semi-transparent materials have also been used. Various clever profiles have been developed to respond to the changing solar altitude angle. Others are adjustable, to compensate for the summer-winter difference in the sun’s path.

Fig.8.1 Light shelves

Fig.8.2 The ‘Valra’ system of light shelves with seasonal adjustment
One major problem with such light shelves is that they may work well, when new, but the upward facing reflective surface rapidly deteriorates as dust deposits form on it. Maintenance and cleaning may prove to be difficult, especially with external light shelves. There were attempts to enclose the reflective surface in a space which can be kept clean, such as the ‘Valra’ system shown in Fig. 8.2. This employs a reflective flexible film, which can be adjusted as required. The illustration shows its two extreme positions. This works well both for lighting and as a shading device.

### 8.2 Reflective louvres

The principle of these is the same, except that the one large reflective surface is divided into numerous narrow strips. The louvre blades may be fixed, but because of their smaller size, it is easier to provide adjustability. Such adjustment may be manual, but often it is motorised and pre-programmed, or responsive, i.e., controlled by light sensors.

While their effect is similar to that of the light shelves in terms of directing light to the ceiling, their shading effect does not extend much below the lowest louvre blade. It is easier to ensure the durability of reflectiveness, e.g., by enclosing the louvres between two panes of glass.

### 8.3 Prismatic glazing

A prism redirects light by refraction. The most common prism is of a triangular cross-section, but prisms of trapezoidal cross-section may have the same effect: a beam of light is deflected towards the thicker side of the prism. A prismatic glass (or transparent plastic, e.g., perspex or polycarbonate) is a grooved sheet with narrow strips of a prismatic cross-section. Normally one side is smooth, the other side has a pattern of saw-tooth section.

A prismatic sheet can be included between the two panes of a double glazed window, usually in the upper part (about 1/3 of the height) of the window or indeed the prismatic sheet can form one of the double glazing panes (with the smooth side outwards). Its effect will be very similar to that of the light shelf: the sunlight beam is redirected towards the ceiling. With overcast sky the effect is barely noticeable.

In a more sophisticated version the prismatic sheet may be in a separate frame, which is hinged and can be adjusted, responding to the sun's apparent movement and may be utilised as a shading device.

One sub-category of this is the prismatic film: with a thickness of a fraction of a mm, but otherwise similar to the above. It is often produced in a self-adhesive form, so it can be easily applied to the surface of the window glazing.

### 8.4 Holographic systems

These achieve the same purpose as the above. Diffraction is created by microscopic structures. Holographic optical elements can be used either in fixed or moveable form, with an effect very similar to that of light shelves. Their rainbow-effect from certain directions can be decorative or can be annoying (depending on the viewer's attitude).
8.5 Light pipe systems

The system has three main parts:

- the heliostat
- a light conduit
- an emitter in the room.

The system is only suitable for sunny climates, as it does not respond to diffused light. The essence of its operation is that it collects and concentrates sunlight, conducts it to the desired point in the building and emits it through a diffuser. The simplest system may serve one emitter, but larger, multi-point systems have also been constructed. (Such systems are possible without concentration, but are not very effective.)

The heliostat is driven by a tracking mechanism to follow the sun and its collector directs the sun's light-beam to a stationary receiver. The collector may be a mirror, often concave, or a tracking Fresnel lens or a rotating double prism plate system. The receiver may be another mirror (as in Fig.8.3) but could be a lens; the aim is to produce a collimated beam of concentrated light.

The conduit may be a metal tube with polished, highly reflective internal surface or a duct with similar lining. Tapping-off mirrors may direct some of the light into sub-conduits, such as that shown in Fig.8.4. Optical fibres have also been used as light conduits.

The emitter is similar to an electric lighting luminaire. It distributes the parallel light beam into the room, and by choice it can be direct, semi-direct, general diffusing, semi-indirect or fully indirect.

The efficiency of the system is primarily dependent on the light conduit, its quality and its length. Concentration and collimation of the light, as well as the cleaning and maintenance of the light pipe are very important. The efficiency of a good system can exceed 25%, measured from the sunlight incident on the primary collector, to the light emitted into the room.
A commercially available ('Daytracker') heliostat application is shown in Fig. 8.5. It uses one motorised plane mirror, one Fresnel lens and a pyramid-shaped plastic diffuser.

A simple version of the light tube ('Sola-Tube', Fig. 8.6) is quite popular for domestic use, especially for internal bathrooms, corridors or hallways of houses. This has a perspex dome (of some 250 mm diameter) on the roof, with a polished aluminium ' adaptéor' inside, which may reflect some low-angle sunlight into the tube.

8.6 Laser cut panels

A thin sheet of clear acrylic plastic may be converted into a light reflecting panel by making a series of fine laser cuts through or partly through the acrylic (Fig. 8.7a). The deflection of light is due to both refraction and total internal reflection working in the same direction (Fig. 8.7b) and is much more powerful than what can be achieved by prismatic glazing or reflective louvres. The sheets can be as thin as 3 mm and the fabrication by automatic laser cutting machine is suited to the production of small quantities of panels in almost any size and shape. Panels not cut through can be exposed to the weather. Less control of the laser cutting is required if the cuts are made right through the panel, but in this case the panel must be protected by mounting it inside (perhaps existing) glazing or by lamination between glass sheets.

The simplest application is the fixing of these panels as double glazing to the upper half or third of existing glazing. The window then performs as a light shelf, directing the light to the ceiling. If the laser cuts are made at an angle (typically about 10°) then the light is directed more deeply into
Fig. 8.7 (a) A light deflecting panel produced by dividing a clear acrylic sheet into an array of elements by laser cutting. (b) Refraction and total internal reflection in each element of the array

The same effect is achieved if the panels are fitted into hopper type windows (bottom hinged) which may be tilted to optimise daylight penetration into the room.

If the panels are incorporated in a conventional horizontal louvre fitting, an extremely effective radiant heat control and daylighting system is obtained. With the louvres in a fully open position the high angle sunlight is deflected to the exterior, whilst the louvre allows an almost unobstructed view to the outside as well as ventilation. This is the best configuration for tropical climates. In winter the louvres are closed and the radiation is directed to the ceiling, providing both controlled daylight and radiant heat gain (Fig. 8.8a and b).

Skylights may be utilised more efficiently in sub-tropical areas by incorporating laser-cut panels in the glazing of a pyramid toplight: This will reject the radiation around the middle of the day (high angles) and improve the penetration of low angle sunlight (Fig. 8.9). The resulting light input is more uniform over the day and overheating near noon in summer is avoided.

Fig. 8.8 Laser cut panels in louvre configuration (the view is maintained in both cases)

Fig. 8.9 A pyramid of laser cut panels inside a clear pyramid skylight: rejects high angle light and admits it from a low angle

The Editor is grateful to Dr Ian Edm for contributing this Section 8.6
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