1 Introduction

1.1 Light in architecture

In contemporary architecture excessive use is made of artificial systems, and architecture is seen as glass geometry, with paradoxical curtain walls that instead of communicating with the exterior, create impractical barriers. A point is thus reached where the interior environment, which is theoretically controlled, can become more inhospitable than the exterior, so that architecture works 'worse than the climate'.

Providing a building with natural light is more than just the solution of a problem of energy consumption; more, even, than an aesthetic resource easily incorporated into the architecture. Natural light in architecture must be part of a more general philosophy that creates a more respectful, sensitive attitude in human beings towards the environment in which they live.

2 Basic physical principles

2.1 Electromagnetic radiation

Electromagnetic radiation is a form of energy transfer by means of periodic variations in the electromagnetic field, and can also be interpreted as the movement of particles (photons).

Different forms of electromagnetic radiation are classified according to their wavelength or frequency into a number of zones of what we call the radiant spectrum, according to their effects(Fig 4.1). In this spectrum, visible light occupies an extremely narrow band.

It is important to bear in mind that the wavelength ($\lambda$) and the frequency ($f$) of the propagation of a vibratory movement are related to the speed of propagation ($c$) thus: $\lambda = c/f$.

Electromagnetic radiation is caused by variations in the atomic structure of bodies, when the orbital position of the electrons is altered. On returning to their original position they cause photons to be emitted, the excess energy thus being eliminated in the form of radiation.

There are two main types of radiant sources, discharge and thermal sources, although for the purposes of natural light it will suffice to consider the latter.
Thermal sources emit radiation as a result of the thermal agitation of matter, and display a characteristically continuous spectrum in the field of wavelengths they cover.

At room temperature sources emit infrared radiation, but as the temperature of the emitter rises, not only does the amount of energy emitted increase but also the maximum wavelength of the peak of emission moves towards increasingly shorter wavelengths. In this way, as the radiation temperature increases it moves further into the visible band of the spectrum, until, at a temperature of around 6500 K, the maximum is located in this zone. It is no coincidence that this temperature is approximately that of the surface of the sun; the field of activity of human sight is adapted to the highest values of radiation in our planetary environment.

### 2.2 Units and fundamental equations of light as energy

In lighting, four main units are used to describe light and its effects.

**Luminous flux**

measures the amount of light per unit of time, and is abbreviated as \( \Phi \). Its unit of measurement is the lumen (lm).

**Luminous intensity**

measures flux in a given direction, and is abbreviated as \( I \). Its unit of measurement is the candela \( (cd = \text{lm}\text{str}^{-1}) \) (str: unit of solid angle in which the surface subtended on a sphere is equal to the square of the radius)

**Luminance**

indicates the lightness of an emitting surface for an observer, and is abbreviated as \( L \). Its unit is the candela per square metre \( (cd\text{m}^{-2}) \).

**Illuminance**

measures the flux reaching a given surface, and is abbreviated as \( E \). Its unit of measurement is the lux (lx).
In any light phenomenon it can be observed that the light originating from an emitting source expands through space, and as it moves away from its source the illuminance that it produces on a surface decreases by the square of the distance. Equally, if the surface is not orthogonal to the incident beam, the illuminance decreases by the cosine of the angle of deviation, resulting in the following:

\[ E = \frac{I}{d^2} \cos(\alpha) \]

In the case of direct solar radiation, given the great distance of the emitting source, variation due to distance is negligible on the Earth’s surface and the beams are considered parallel, which means that \[ E = I \cos \alpha \]

### 2.3 The visible spectrum

Light not only transports energy but also has colour, as a result of the distribution of energy over the different wavelengths of the visible spectrum; a specific colour corresponds to each wavelength, as in the colours of the rainbow. Sunlight covers all the zones of the spectrum and is sometimes referred to as ‘white light’.

In the field of lighting technology specific units are used to indicate the chromatic characteristics of light, thus:

**The colour temperature**
(T_c) expresses the colour of a source of light by comparing it with that of the light issued by a black body at a given absolute temperature (Kelvin: K). Black body changes spectrum according to temperature, at around 3000 K the light is reddish (incandescent lamps), and at higher temperatures it is bluish. T_c is the temperature to which a black body must be heated for the light it emits to be of a comparable colour to the measured light. In natural light its colour temperatures are in the order of 6000-6500 K, the sun’s corona temperature.

The colour rendering index
Expresses the reproductive capacity of light on the colour of the illuminated objects is abbreviated as R and expressed as a percentage. In order to have good chromatic reproduction, light must have energy on all wave-lengths, as is the case with sunlight (in practice its R is 100%).

2.4 Light and space limits
Reflection- Transmission- Absorption
Light is propagated through space; on encountering a material obstacle is partly reflected and partly absorbed by the surface, and some of the light may also be transmitted through the obstacle. The coefficients of reflection (r), absorption (a) and transmission (t) give respective ratios for the incident light that is reflected, absorbed and transmitted by a given surface. The sum of the three coefficients will always yield unity: r + a + t = 1.

As energy can be reflected qualitatively in a different way depending on the type of surface, we shall consider the different possible types from both the spectral and geometric viewpoints.

a) from the spectral viewpoint, surfaces can display different behaviour for the different wavelengths within the visible zone, and white light can take on various colours on being reflected or transmitted by coloured surfaces or materials.

The specific reflectance or transmittance (r, or t,) determines the behaviour of a given surface for light of a given wavelength (with its associated colour). The mean weighted value of r, or t, for a given radiation (in this case sunlight) will give us the value of the reflection coefficient of the surface. The radiation reflected or transmitted by a surface reproduces the spectrum of the incident radiation, modified by the values of the various specific reflections or transmittances (r_l or t_l).

Figure 4.3.- Spectral transmission through a tinted glass
b) from the geometric viewpoint, the finish and the internal structure of bodies can affect the geometry of the transmission or reflection. If the surface irregularities are of a similar order of magnitude to the wavelength of the light, the light will be diffused. If these irregularities are smaller, specular reflection or regular transmission will occur. In practice, three basic types of geometric behaviour can be distinguished.

As the wavelength of light radiation is very small, most surfaces with which we work in architecture are opaque and give mostly diffuse reflection. Only highly polished surfaces and those with an ordered internal molecular structure (crystals) give true regular reflection and transmission.

In the case of pure diffuse reflection or transmission, the resulting distribution of the light is such that the luminance \( L \) of the surface, observed from any direction, is constant and has the value:

\[
L = \frac{E_r}{\pi} \quad \text{or} \quad L = \frac{E_t}{\pi}
\]
In architecture this behaviour tends to distribute natural light more uniformly around interior spaces. Surfaces with regular (or specular) reflection can be useful for reflecting light, especially the direct radiation of the sun, in particular directions considered appropriate. Equally, transmitting surfaces (most commonly glass) are normally of regular transparency, thus allowing the entry of direct sunbeams without varying their geometry and at the same time permitting an external view, usually considered a favourable effect.

3 The physiology of vision

3.1 The eye and sight (visual perception)

The sense of sight is based on the functioning of the eye. This organ features the pupil, which regulates the amount of light entering the eye by means of an opening the surface area of which can be adjusted in a ratio of 1:16. The more closed the pupil is, the less energy enters, but the vision is sharper and with a greater depth of field. The transparent lens changes shape to regulate the focus, maximum deformation occurring with near vision. From the lens, the light crosses the vitreous humour that fills the eyeball and so strikes the retina, where the images focused by the lens are formed. This retina is sensitive to the amount of light by means of cells called rods, and to the amount and the colour (wavelength) of the light by means of other cells called cones. In the centre of the retina there is a small concavity called the fovea centralis, containing only small, tightly packed cones. This is the region on which is the centre of attention and in which the vision is most acute.

*Figure 4.5.- Structure of the human eye*

The human eye responds to the amount of energy it receives with sensations that do not correspond linearly to the stimulus. As is also the case with the other human senses, sight follows an approximately logarithmic law according
to which equal increases in the stimulus do not imply equal increases in
sensation:

\[ S = K \log E + B \]

Where:

- \( S \)  
sensation

- \( E \)  
stimulus

\( B \) and \( K \)  
constants

This type of reaction means that when assessing the effects of light, a given increase has a different value depending on the level of departure. Thus, an increase of 1 m\(^2\) in a window opening seems to have a huge effect if the original opening measured 1 m\(^2\), whereas an increase of 1 m\(^2\) in a 10 m\(^2\) of window results in little sensation of increased light, though the actual increase in illumination is equal in both cases.

In addition to the pupil’s mechanism, sight can adapt to different energy levels using other systems. The cells of the retina work in various fields; the rods are the only cells that register luminance below 10 cd m\(^{-2}\), just as only cones respond in conditions above 300 cd m\(^{-2}\): between these limits, the two types work together.

In vision by means of the cones, light sensitivity is greatest in the yellow region, and is called photopic vision. In vision using the rods (scotopic vision), colour is not registered, and maximum sensitivity is located in a zone with a shorter wavelength.

*Figure 4.6.* - Sensitivity curves of the human eye
The sensitivity curve of the eye with photopic vision is used to define the units. The luminous flux results from affecting the total radiant flux by the sensitivity coefficient of the eye for each wavelength.

\[ F_I = F_r \times V_{680(I)} \]

Where:

- \( F_I \) luminous flux in lm
- \( F_r \) radiant flux in W
- \( V_{(I)} \) sensitivity coefficient

### 3.2 Temporal sensitivity of vision

The human senses tend to adapt constantly to stimuli and to be sensitive according to the mean energy values of their perceptual field. In order to adapt to a change in the conditions of mean luminance of the visual field, the eye needs a period of time which varies according to whether the change is from light to dark or vice versa. More than 30 min is generally considered to be necessary for good adaptation when changing from light to dark conditions, compared to just 30 s or so to adapt from darkness to light. Perfect adaptation from light to dark is a matter of hours, but the first instants are the most noticeable.
This phenomenon is important in architectural design, especially considering that correct perception depends more on the balance of luminance in the field of vision than on the absolute level, since the eye possesses a capacity for adaptation over an extremely wide range of energies, with correct rendering from mean luminance as low as 50 up to 25,000 cd m\(^2\). For this reason, the absolute value of light levels in architectural spaces is often less important than it is for the user to be able to move gradually between different light levels and thus adapt.

3.3 *The spatial perception of the human eye*

The human eye has an approximately hemispherical field of vision (\(2\pi\) stereoradians), with a narrow, central solid angle of precise vision, corresponding to the location of the cornea in relation to the retina. Towards the edges of the visual field, vision is blurred, the perception of shapes rapidly being lost, but sensitivity to remains more or less intact.

Our eyes are usually in constant movement, switching our precise vision from one area to another of the visual field. The movement of the head complements our visual perception of our environment, but there always remains an eclipsed area at our rear which requires the aid of our sense of hearing if we are to feel in control of our surroundings. For this reason, the position of people in relation to the space they occupy can be important, especially in interiors with acoustic difficulties.
Our sense of sight also allows us to pinpoint the direction of the objects that surround us, basically by directing the head and eyes towards that which we are observing. The action of the muscles informs the brain of the direction in relation to our body, to a large extent on the basis of experience.

Judging distance is more complex, and involves a number of mechanisms. Firstly, there is the deformation of the lens as it focuses the image, which makes it possible to judge very short distances. Furthermore, binocular vision, with the difference between the images that each eye perceives, enables us to recognize the relative location of the objects in our field of vision, while at the same time the convergence of the eyes assists us in judging short distances. Finally, it is the learning process that contributes most to informing us how far away objects are located, as we simply weigh up their apparent size on the basis of previous experience. The only drawback to this is that it is an unreliable system in novel environments or ones with a different scale to normal.

3.4 Visual comfort

When we talk of comfort we mean well-being or lack of discomfort in a given environment. Several different causes may be involved in this concept, since all the senses are receiving stimuli simultaneously, in addition to which, other, less recognisable, factors are at work. Nevertheless, comfort is traditionally analysed independently for each of the senses, including sight.
On the subject of comfort we make a distinction between comfort parameters, measureable values of the physical environment, and factors which depend on the user and influence the appreciation of the parameters. Comfort depends on the relationship between the two, and although architectural design essentially affects the physical parameters, the characteristics of the user (age, type of activity, etc.) must be taken into account in order to ensure good design.

Illuminance.

Visual comfort depends on how easily we can see that which interests us. As a result, the primary requirement is that there must be the right amount of light. So the first parameter is illuminance (lx), with recommended values depending on the task and on the glare conditions (which constitute the second parameter to be considered in visual comfort).

Glare

Glare, considered as a comfort parameter, is the unpleasant effect caused by an excessive contrast of luminance in the visual field. As a rule, this effect is due to the existence of a small area of great lightness (luminance) in a field of vision with a considerably lower mean value, normally as a result of a lamp or a window.

The 'adaptation glare', is the more important in architectural design, and is caused when the eye adapts to the mean luminance of a visual field where there is a great variation in luminance, with extremes that are outside the capacity for visual adaptation and are therefore cannot be seen properly.

Glare can also be classed according to the incidence on the eye of a beam of excessive light. When it strikes the fovea centralis it is called direct glare, or incapacitating glare. If the incidence is elsewhere on the retina it is called indirect glare (also called disturbing or perturbing glare). In many cases the same terminology (direct/indirect) is used to distinguish the glare produced directly by a light from that produced by a reflection on a surface (such as a glass-topped table).

Glare is difficult to evaluate, although this can be achieved by analysing the various different values of luminance in the field of vision. As a first approximation, the values recommended as suitable are: contrasts of 1-3 between the observed object and its immediate background, 1-5 between it and the work surface as a whole, and 1-10 between it and other surfaces in the field of vision. In a more accurate analysis, the following concepts are brought into play:

\[ g = \frac{L_s^a \omega^b f(\theta)}{L_B} \]
where:

$L_s$
luminance of light source

$\omega$
solid angle of the source from the eye

$f(\theta)$
function of the direction from which the light arrives
(value 1 if it arrives perpendicularly to the eye and 0 if it arrives laterally

$L_B$
luminance of the background to the light source

$a$ and $b$
coefficients with typical values 1.8 and 0.8

Glare grows as the value of this glare constant $g$ increases. As discomfort
approximately follows the logarithmic law, the glare index ($G$) is defined thus:

$$G = 10 \log_{10} g$$

When the value of the index $G$ exceeds 10 the glare is noticeable, from 16 to
22 it is bearable, from 22 to 28 it is uncomfortable, and for higher values,
intolerable. With daylight there is a greater tolerance of glare than with artificial
light.

**Colour of the light**

A third parameter for visual comfort is the colour of the light; derived from the
concepts of colour temperature and colour rendering index, discussed above.
The Kruithof graph establishes a relationship between the colour temperature
of the light and the illuminance, and defines a field of compatibility between
the two values. In natural lighting the colour of the light will have little
influence on comfort, since its chromatic characteristics are taken as the
theoretical ideals.

Considering all the above we can state typical values for light parameters in
relation to the factors of the user (Tables 4.1 - 4.5)

<table>
<thead>
<tr>
<th>Light definers</th>
<th>Illuminance (general values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities with very high eye strain: precision drawing, jewellery etc.</td>
<td>1000 lux</td>
</tr>
<tr>
<td>Short-duration activities with high or very high eye strain: reading, drawing, etc.</td>
<td>750 lux</td>
</tr>
</tbody>
</table>
Short-duration activities with medium or high eye strain: work in general, meetings, etc.
500 lux

Short-duration activities with low or medium eyestrain: storage, movement, etc.
250 lux

Table 4.2
Modifying factors for the general illuminance values

<table>
<thead>
<tr>
<th>x 0.8</th>
<th>x I</th>
<th>x 1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age &lt; 35 years</td>
<td>Age 35-55 years</td>
<td>Age 55 years</td>
</tr>
<tr>
<td>Activity unimportant</td>
<td>Activity important</td>
<td>Activity critical and unusual</td>
</tr>
<tr>
<td>Low difficulty</td>
<td>Normal difficulty</td>
<td>High difficulty</td>
</tr>
</tbody>
</table>

Table 4.3
Luminance values (with corresponding illuminance)

<table>
<thead>
<tr>
<th>Visual code</th>
<th>Luminance (cd m(^{-2}))</th>
<th>Horizontal illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human face hardly visible</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Face fully visible</td>
<td>10-20</td>
<td>200</td>
</tr>
<tr>
<td>Optimum for normal work</td>
<td>100-400</td>
<td>2000</td>
</tr>
<tr>
<td>Surfaces with reflection &gt; 0.2 well lit</td>
<td>&gt; 1000</td>
<td>20,000</td>
</tr>
</tbody>
</table>

Table 4.4
Glare indices (G)

Highly critical conditions with difficult work, dangerous situations, etc. Imperceptible: < 13

Low: 13-16

Medium: 16-19

High: 19-22

Very high: > 22

Table 4.5
Colour of the light

<table>
<thead>
<tr>
<th>Type of space</th>
<th>Condition</th>
<th>R (%)</th>
<th>T(_c) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spaces where colour is very important</td>
<td>Work</td>
<td>&gt;85</td>
<td>4500-6000</td>
</tr>
<tr>
<td></td>
<td>Rest</td>
<td></td>
<td>2500-</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spaces where colour is important but not critical</td>
<td>Work</td>
<td>70-85</td>
<td>&gt; 4000</td>
</tr>
<tr>
<td></td>
<td>Rest</td>
<td></td>
<td>&lt; 4000</td>
</tr>
<tr>
<td>Spaces where chromatic recognition is unimportant</td>
<td>Work</td>
<td>&lt;70</td>
<td>&gt; 4500</td>
</tr>
<tr>
<td></td>
<td>Rest</td>
<td></td>
<td>&gt; 4500</td>
</tr>
<tr>
<td>Space without chromatic vision</td>
<td></td>
<td>40</td>
<td>Indifferent</td>
</tr>
</tbody>
</table>
3.5 Biological effects

Today daylighting requirements are depending on two aspects, the visual perception and the biological effects. The higher the illumination is the easier it is to do optical activities and older people need higher illuminations than younger people. According to Lange the highest user acceptance for illumination is between 2000 Lux (lx) and 4000 lx. Minimum values as well as additional requirements are given in corresponding standards (EN 12464).

Since the discovery of a third lighting receptor on the retina (additional to the cones and rods which are responsible for vision) in the year 2002, the biological effects of light on the human organism, which had been suspected for a long time, could be assessed. Compared to the brightness sensitivity of the eye for optical functions, the sensitivity of this sensor is in the blue zone. So far studies show that illuminations higher than 1000 lx will influence the biological clock of humans for diurnal and annual cycles with sleeping and wake phases and will affect brain activity, well being and health. These insights require a new benchmark for “good light”.

Minimum requirements for shading devices and summer heat insulation are defined to avoid high summer room temperatures (or respectively high cooling loads in case of cooling systems), and should be achieved without adverse effect on daylighting. In view of the new and remarkable perceptions about the biological properties of daylight this is a challenge for the design of windows: Small thermal solar admission into the room while at the same time allowing high illumination levels (> 1000 lx).

4 Daylighting in architecture

4.1 Indoor and outdoor light

Architecture is basically a juxtaposition of indoors and outdoors, sheltered space and exposed environment, confidence and vulnerability, privacy and society. During the day, natural light reveals the entirety of the exterior, filling all its corners and crudely showing the skin of buildings, their size, shape and details.

When light is used wisely in architecture it enters from outside the visual field of the observer, through high openings often located above the entry to the space. This restoration of an interior light of its own, from an unidentified source, exerts a rather magical effect. It renounces the external view in exchange for the reorganization of the interior space, which ceases to be secondary.

This whole situation changes radically at night, when the roles of the interior and the exterior are inverted. At this point two brief comments can be made on the use of artificial and natural light in architecture.
1. Both architecture and we who inhabit it are different by day and by night, therefore it makes no sense to try to imitate the effects of natural light with artificial light; the results will always be mediocre.

2. It is always difficult to combine the two kinds of light, due to their different chromatism and the fact that when the eye is accustomed to natural levels of light it finds artificial light poor and gloomy.

Returning to natural light as energy passing from the exterior to the interior of the building, it should be borne in mind that the way in which it enters is conditioned by its origin, which can be threefold:

![Figure 4.8.- Three incidences: direct sun, sky dome and albedo](image)

Direct sunlight strikes with parallel beams of light with a high luminous flux (as high as 100,000 lux). Indoors it generates clearly defined patches of light that change as the sun moves across the sky vault. This type of light therefore creates uncomfortable interior visual conditions caused by excessive contrast, and easily results in overheating in interiors. Its thermal effect and its unique distribution of luminance, which imparts a feeling of cheerfulness, are desirable in winter and in cold climates and undesirable in summer in hot climates.

Sky dome light is associated with an overcast sky (though it is also the case in clear skies for directions facing away from the sun), and is the most usual form of natural light in Atlantic and northern climates. Its lighting intensity is 5 - 10% of that of direct sunlight. The amount of light from a cloudy sky depends on the sun altitude and the cloud density and so can vary considerably. This condition is often used as a minimum condition, but one must also consider that, in hotter climates, its entry into the building can cause overheating problems.

Reflected or albedo light from external surfaces becomes important when the other two types lack intensity, either because they are excluded to avoid overheating or because the form of the building does not allow direct access to skylight. In these circumstances, and when the external surfaces (the ground and neighbouring buildings) have relatively high reflectance, albedo light can generate useful interior lighting, although it should always be remembered that since the light is not coming from above it has a greater tendency to cause glare.
4.2 The perception of light in architecture

When an architect imagines the architecture that he is beginning to design, he pictures in his brain the forms of the building he is creating, from overviews of the building to specific details of its façades.

If we look at the works of the great masters of architecture, both ancient and modem, it is clear that in most cases natural light was present from the very first images of the projects they conceived.

It is interesting to observe the different approaches architects have to natural light. Quite apart from the greater or lesser knowledge they may have of the basic principles of lighting and even without assessing the efficiency of the results obtained, it appears that each one of them intuitively conceives the phenomenon of light differently, and this is reflected in the way in which light defines and shapes the spaces of their architecture.

In many cases light is imagined as a fluid, liquid or gas that occupies all external space and spills or expands (according to how it is conceived), through the light openings and into the interior space.

In other cases, light is understood as beams, in an almost mythological image of celestial force travelling through space, penetrating the interior and bouncing off surfaces, thus imbuing them with reality.

On other occasions natural light plays an impressionistic game in an interior, independent patches of light only coming together to form a whole in the brain when the space is perceived globally. In such cases colour is decisive, and wall surfaces change the tone of the light they receive.

4.3 Lighting in peripheral and core zones

The first point to tackle when considering the use of natural light is its entry into interiors that would otherwise be dark, due to the fact that they are separated from the exterior by a façade.

In any building, two separate problems can be distinguished: the lighting of the peripheral zones, which have contact with the skin of the building and therefore the possibility of direct access to the light outside; and that of the interior zones, where the only access to natural light is by means of some system of transportation.

However, before dealing with specific systems applying to the periphery or the core, we shall consider some general aspects of the project that affect its interrelation with light.

Compactness

One initial point to consider is the compactness of the building, which establishes the relationship between the outer shell of the building and its volume, i.e., the degree of concentration of the interior spaces. Logically, less compact buildings will have greater possibilities of natural lighting, as the core
zone, where the entry of light is more difficult to achieve, is correspondingly smaller.

**Porosity**

Another aspect to be taken into account is the porosity of the building, which refers to the existence within its global volume of empty spaces and points of communication with the exterior, such as courtyards. A high degree of porosity indicates the possibility of creating an access for light (and also ventilation) in the core zones of the building.

**Transparency**

A further general aspect to consider is the transparency of the skin of the building to light, which varies from totally opaque buildings to totally glazed ones. Although greater transparency increases light in the peripheral zone, good lighting depends more on the appropriate distribution of light than on quantity.

**Geometric characteristics**

Other aspects to take into account are the geometric characteristics of the interior spaces. Premises can thus be analysed according to size, shape, proportions and possible differences in floor level.

**Size of a building**

Though size does not in principle have any influence on the distribution of light in its interior; areas of identical shape but different size and with their openings to scale with their size will have the same interior light distribution. The only point that should be borne in mind is that spaces with large surface area will have a dark central zone unless they have a higher ceiling.

![Figure 4.9.- Central zone in spaces with a large surface area](image)

**Shape and proportions**

In a building they are important for its natural lighting, depending on the location of the windows. As a rule, irregular or elongated spaces with light entering at the end have a rather irregular light distribution.

![Figure 4.10.- Relationship between shape and light distribution](image)
It should be remembered that the lateral entry of light into a space causes a rapid decrease in light (i.e., illuminance) the further we are from the opening, due to the fact that the direct vision of the sky (the main source of light) is soon lost. This results in peripheral zones and premises easily being badly lit, even if the total amount of light present is sufficient. Light from the zenith on the other hand, tends to be greater but is more hard to achieve.

5 Daylighting improvement in buildings

5.1 Transmitting elements

These are spaces that are located beyond a room that initially receives natural light from the exterior. They collect the light transmitted through the outer room and so on. The shape of such an outer room is very important, since their capacity to transmit the light they receive depends to a large extent on the geometric characteristics of the space.

The characteristics of the finish on their surfaces are also important, as this is where the natural light strikes. Different finishes cause rooms to act differently according to whether they are reflecting, specular, diffuse, absorbent or whatever.

5.1.1 Intermediate light spaces

These are located in the peripheral zone of the building, between the external environment and the inhabitable spaces. They can act as regulatory filters between the internal and external environmental characteristics; they guide and distribute the natural light that reaches them from the exterior to the interior. They are sealed with transparent or translucent materials and can incorporate...
control elements to regulate light passing through. The most typical example are galleries, porches and greenhouses

5.1.2 Interior light spaces

These form part of the interior zone of a building, guiding the natural light that reaches them to interior inhabitable spaces that are far from the periphery. Within this group are courtyards, atria and all types of light-ducts and sun-ducts.

5.2 peripheral and core elements

These are devices or sets of elements that connect two different light environments separated by a wall containing the element. They are defined by their geometric characteristics, namely, their size in relation to that of the wall in which they are set, their position in that wall (central or lateral, high or low) and the shape of the opening. Their composition depends on the elements they incorporate to control and regulate the lighting, visual and ventilation phenomena.

5.2.1 Lateral transmitting elements or apertures

These are located in vertical enclosing surfaces, either in the skin of the building or in internal partition walls, between two environments with different lighting characteristics, and permit the lateral entry of light to the receiving area. Typical lateral transmitting elements are windows, balconies, translucent walls and curtain walls.

5.2.2 Zenith transmitting elements or apertures

These are located in horizontal enclosing surfaces in the roof or the interior of a building, between two different light environments, and are designed to let zenithal light into the receiving environment below. Typical zenithal transmitting elements in architecture are clerestories, monitor roofs, north-light roofs, translucent ceilings, skylights, domes and lanterns.

5.2.3 Global transmitting elements or apertures

The most typical element of this type is the membrane, with translucent or transparent surfaces, which surrounds the whole of an interior environment. It allows overall entry of light and generates a high, uniform light level in the interior, similar to external conditions.

5.3 Control elements

5.3.1 Separator surfaces

These are surface elements of transparent or translucent material, incorporated into a transmitting element that separates two different environments. They enable radiation, and sometimes the view of the exterior, to pass through, but
block the passage of air. Among the numerous types of separator surface in existence in the field of architecture, there are conventional transparent ones (Glass etc), those with chemically or mechanically treated surfaces, those that follow a particular geometrical pattern and active enclosing surfaces.

5.3.2 Flexible screens

These are elements that partially or totally prevent the entry of solar radiation and make the light that shines through them diffuse. Depending how they are placed, they can allow ventilation and provide visual privacy. They can be retracted, rolled up or folded away to remove their influence when so wished. The commonest types of flexible screens are awnings and exterior curtains.

Awnings and curtains are made of materials that are either opaque or serve to diffuse light. They can be placed over the external surface of a transmitting element, so as to selectively prevent radiation passing prior to entry or, by placing them over the interior of separator surfaces, control the radiation that has already entered the transmitting element and is illuminating the interior.

5.3.3 Rigid screens

These are opaque elements that redirect and/or block the direct solar radiation that might otherwise strike a transmitting element. Normally, they are fixed and unadjustable, though there may be exceptions to this. Their main variable is their position with relation to the opening they protect. Among the various possible types we shall put special emphasis on overhangs, light-shelves, sills, fins and baffles.

5.3.4 Solar filters

These are surface elements that cover all, or nearly all, of the outer face of a transmitting element, protect it from solar radiation and allowing ventilation. They can be fixed or movable (so that they can be removed and the opening left free), and adjustable if the orientation of the louvers can be changed. Those most used in architecture are the various types of blinds and jalousies.

5.3.5 Solar obstructers

These are surface elements composed of opaque materials, and can be attached to the opening of a transmitting element in order to completely seal it. They are normally called shutters and can be located either on the exterior or on the interior of a glass separator surface.

6 Conditions of the sky

6.1 Sky luminance

The luminance of the sky is a basic characteristic to be taken into consideration when studying the pre-existing conditions of a site. The local climate, with its associated degree of cloud cover, is a decisive factor in this.
There are several different possible models for the luminance of the sky to take into account as a pre-existing environmental condition in a given place. As a rule, an overcast sky is taken to be the most unfavourable case, and often only this is studied. This is logical in northern climates, but not in temperate ones, where the cases of cloudy and clear skies should also be considered, as should the position of the unobstructed sun. Protection from the sun and the exploitation of its radiation both need to be considered.

It should be borne in mind that Mediterranean climates have direct sunlight much more frequently (70% of the time) than more northern climates (30% of the time); this is often neglected when studying the natural lighting of buildings.

6.1.1 Uniform overcast sky

This is the main model used in natural lighting studies, with constant luminance in all directions and heights. The relationship between the mean luminance of the sky and the illuminance of a horizontal plane without any obstruction will be:

\[ E_h = \pi L \]

where:

\( E_h \)

illuminance on horizontal plane (lux)

\( L \)

mean illuminance of the sky (cd / m²)

<table>
<thead>
<tr>
<th>Table 5.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>The values for the mean luminance of the sky dome for latitude 40°, with different climatic conditions and times of year</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Hours</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Lumin.</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The values in the first row correspond to mean luminance with an overcast sky, while the second row is for a clear sky. The minimal case at Mediterranean latitudes is taken to be an overcast sky with 3200 cd m⁻², which is equivalent to some 10,000 lux on a horizontal plane without obstructions.

6.1.2 CIE overcast sky
This is the model for the standard overcast sky, which provides a better fit with reality, since luminance varies with height. This relationship is defined with the Moon-Spencer formula:

\[ L_\alpha = \frac{L_z (1+2 \sin \alpha)}{3} \]

where:

\( L_\alpha \)

luminance at a height with angle \( \alpha \) above the horizon

\( L_z \)

luminance at the zenith

\( L_z \) can be considered to be \( 9/7 \) of the (uniform) mean luminance of the sky.

Another correcting factor to be taken into account is the variation of the luminance of the sky depending on direction. This luminance variation can be expressed, for the horizon, as a 20% increase in the direction of the equator and likewise a 20% decrease in the direction of the pole. These variations diminish with height, disappearing at the zenith. The Moon-Spencer expression, duly corrected to allow for this variation, would be:

\[ L_{\alpha,\beta} = \frac{(L_z (1+2 \sin \alpha))}{3(1+0.2 \cos \beta)} \]

where:

\( L_{\alpha,\beta} \)

luminance of the sky for a height \( \beta \) in the direction of the equator

\( L_z \)

luminance at the zenith

### 6.1.3 Clear sky

For the case of a clear sky the best strategy is to consider only the direct incidence of the sun, with intensity in the order of 100,000 cd m\(^{-2}\) and the position corresponding to the time of the year and day. We will also consider,
as indirect sources, the rest of the sky dome and reflection from other surfaces on the ground or other external elements (albedo).

For the case of a clear sky dome, luminance decreases as we move away from the sun, with values varying between 2000 and 9000 cd m\(^{-2}\).

For the case of the albedo, the typical luminance value is taken as the result of applying the following expression:

\[
L_a = \frac{E_h r}{\pi}
\]

where:

- \(L_a\) luminance of albedo
- \(E_h\) illuminance received by the surfaces (100,000 lux for a clear sky)
- \(r\) reflection coefficient of the surfaces (typical value of 0.2, or as high as 0.7 on light surfaces)

### 6.1.4 Cloudy sky

In the case of a cloudy sky, intermediate between a clear and an overcast sky, hypotheses must be made which correspond to a situation somewhere between those considered in the above cases.

### 7 Daylighting evaluation in architecture

In natural lighting there is so much variability in the factors that generate the environment that evaluation systems are inexact. Calculations provide us with knowledge of interior conditions in relation to exterior ones which we know to be changing. Because of this, results are expressed as percentages of the exterior level, and are called daylighting factors (DF):

\[
DF = \frac{100 \times E_i(\text{interior})}{E_o(\text{exterior})}
\]
The system for representation of light can be derived from point-by-point values. Using the mesh of points which represents the premises, 'isolux' or 'isoDF' curves can be drawn joining points of equal illuminance or DF value, for fixed values every 50 or 100 lx, or every 2, 5% or 10% DF. These curves, similar to a topographic map, provide good information on the distribution of light in the space.

![Figure 4.12.- Software. Rough analysis for illumination](image)

Generally speaking, natural light calculation systems fall into one of the following categories: predimensioning methods, point-by-point methods and computer-assisted exact calculation. There are also evaluation.

### 7.1 Pre-dimensioning method

The result given is the mean illuminance on a working plane situated just above the floor in an interior space. The formulation is as follows:

\[ E_i = \frac{i}{S_{pas}} \]

where:

- \( E_i \)
  - interior illuminance, in lux
- \( E_e \)
  - exterior illuminance on a horizontal plane, in lux. 10,000 lx (overcast winter day), 100,000 lx (clear summer day)
- \( S_{pas} \)
  - total surface area of openings, in m²
opening factor (solid angle of sky seen from the opening as a proportion of the total solid angle of the sky (2p), on a vertical plane = 0.5)

transmission factor of the enclosing surface (normally < 0.7)

utilization coefficient, or ratio between the flux reaching the lit plane and the flux entering the premises through the opening (value of 0.2-0.65)

surface area of the premises, in m²

7.2 Point-by-point calculation

This method calculates the resulting illuminance for each of the points chosen, which together form a metre-square mesh, and for each of the openings, considered as diffuse emitting surfaces. The basic formulae applied are:

\[ E = \frac{I \cos \alpha}{d^2} \]

where:

\( E \)
resulting illuminance, in lux

\( I \)
intensity reaching the point, in candelas

\( \alpha \)
angle at which the light arrives from the opening

\( d \)
distance from the centre of the opening to the point, in m

\[ I = LS_O \]

where:

\( L \)
illuminance of the opening, in cd m\(^{-2}\) 

\(S_O\)

surface area of the opening, in m\(^2\)

\[ L = \frac{E_O}{\pi} \]

where:

\(E_O\)

illuminance emerging from the opening

\[ E_O = E_e v t \]

where:

\(E_e\)

mean exterior illuminance on a horizontal plane, in lux

\(v\)

opening factor, or solid angle of sky seen from the opening as a proportion of the total solid angle of the sky

\(t\)

global transmission factor of the enclosing surface,

There exist tables and graphic abaci that can be used to calculate \(v\) and \(E\).

### 7.3 Computer methods

These make use of the powers of computer calculation to integrate the results of the light reaching each point from openings and interior reflections alike. In fact they apply the point-by-point system with all the necessary iterations to obtain great accuracy.

### 7.4 Evaluation methods using scale models

The use of scale models in architecture to evaluate natural lighting has a long tradition. Physical models reproduce in miniature the building that it is intended to build, their strength residing in the fact, mentioned above, that
radiant phenomena are stable despite scale changes in space, basically as a result of the short wavelength of light in comparison with the size of spaces.

Scale models make it possible to evaluate complex configurations and shapes which are difficult to reproduce in computer models, and have the further advantage that the resulting light in the space being designed can be visualized easily. The behaviour of the building with regard to light can be tested in different ways: using the real sky or artificial skies.

Nevertheless, it should be borne in mind that evaluation systems, whether they be manual, computer- assisted or using scale models, are no substitute for a sound approach to the project, and this depends above all on the attitude of the designer, which should be based on a good understanding of the physical and physiological principles of light and vision.

REFERENCES

Coch H; Serra R; San Martin R. Arquitectura y control de los elementos (1996) Barcelona Ed. Balmes