LIGHT, VISUAL COMFORT AND GLASSES

Light and visual comfort

Human eye and daylight

Visual perception is the ability to interpret the surrounding environment using light in the visible spectrum reflected by the objects in the environment. The sensitivity of the human eye to light of a certain intensity varies strongly over the wavelength range between 380 and 800 nm. Under daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm, resulting in the fact that green light at this wavelength produces the impression of highest "brightness" when compared to light at other wavelengths. The spectral sensitivity function of the average human eye under daylight conditions (photopic vision) is defined by the CIE[1] spectral luminous efficiency function V(λ), as shown in Figure 1. Only in very rare cases, the spectral sensitivity of the human eye under dark adapted conditions (scotopic vision), defined by the spectral luminous efficiency function V'(λ), becomes technically relevant. By convention, these sensitivity functions are normalized to a value of 1 in their maximum [1].
As an example, the photopic sensitivity of the human eye to monochromatic light at 490 nm amounts to 20% of its sensitivity at 555 nm. As a consequence, when a source of monochromatic light at 490 nm emits five times as much power (expressed in watts) than an otherwise identical source of monochromatic light at 555 nm, both sources produce the impression of same "brightness" to the human eye.

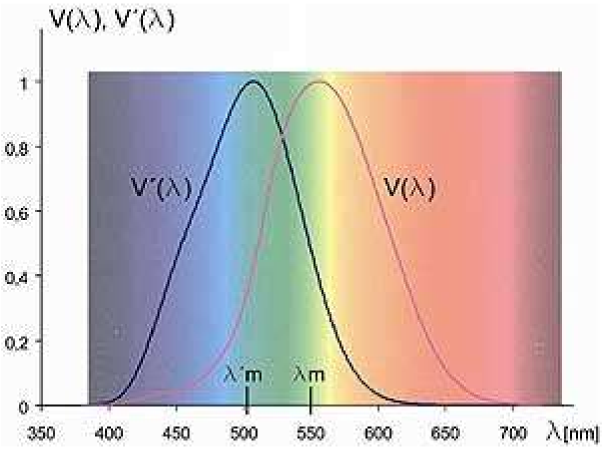


Figure 1. Spectral luminous efficiency functions V(λ) for photopic vision and V'(λ) for scotopic vision, as defined by the CIE [1].

Daylight is the preferred lighting source: it is energy-efficient, flicker-free, dynamic and it has a spectrum that ensures excellent colour rendering. However, a good combination of daylight and artificial light has to be reached, since daylight cannot be the only source,

[1] CIE: International Commission on Illumination

because of its continuous variability, according to weather, the time of day and year and because its intensity decreases as the distance from windows increases. Natural light has positive effects on human beings and these effects can be distinguished in two types: direct and indirect. The direct effects are caused by chemical change in tissues due to the energy of the absorbed light, while the indirect ones are the regulation of the basic biological functions and the production of hormones, connected to light exposure. The regulation of circadian rhythms, seasonal cycles and neuroendocrine responses in many species, including humans, is due to light stimuli [2], [3]. Circadian rhythms are changing patterns that run over a period of approximately 24 hours, trying to establish an internal replication of external night and day: these rhythms are associated with body temperature, alertness and the secretion of hormones, such as melatonin and cortisol (Figure 2). Melatonin is known as the "sleep hormone": it drops in the morning, reducing sleepiness and it rises when it becomes dark. Cortisol is the "stress hormone": its level increases in the morning, falling to a minimum at midnight.

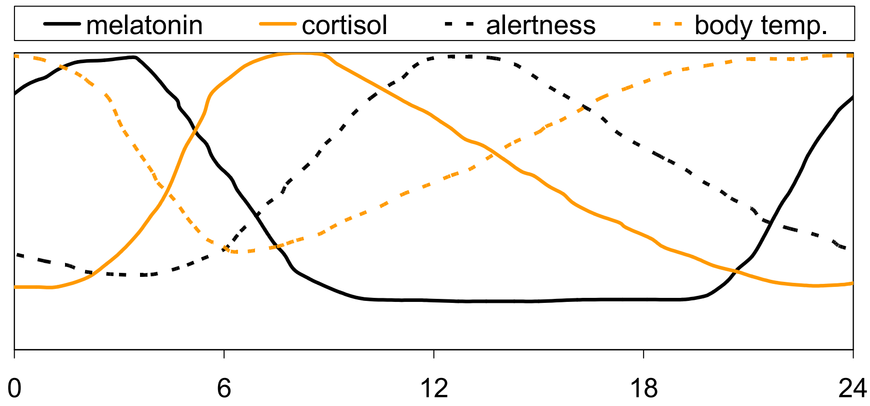


Figure 2. Typical daily rhythms [8].

Shift work may cause a shift of the biological clock that may result in extreme sleepiness, in lack of concentration, increasing the risk of accidents. Manipulation of the circadian system, by means of different lighting conditions, can make people work at times when one would normally be sleeping; this statement is at the basis of the concept of the dynamic lighting. Some researchers have argued that all the physiological processes should work optimally when exposed to daylight, since daylight has been the sole source of illumination for most of the period of humans' evolution [4]. According to this hypothesis, electric lighting should be as similar as possible to daylight.

John Ott [5], [6] was the pioneer of full spectrum light: initial interest in Full Spectrum Fluorescent Lamps (FSFLs) began with observations of plants' growing under different lamp types. FSFLs emit light that is supposed to be similar to daylight over the visible range and some in the ultraviolet-A region of short-wavelength, high energy radiation. However, FSFLs cannot be like daylight, because of the colour temperature (daylight varies in colour temperature from 5000 K to 10000 K, according to sky conditions, season and time of the day), of the illuminance that they provide and of the polarisation of daylight.

Visual comfort and natural lighting

Visual comfort is a subjective reaction to the quantity and quality of light within any given space at a given time. The concept of visual comfort depends on our ability to control the light levels around us. Both too little and too much light can cause visual discomfort. Just as importantly, changes in light levels or sharp contrast can cause stress and fatigue, as the human eye is permanently adapting to light levels. It can vary depending on the following factors: time of exposition, type of light, the colour of the eye (light-coloured eyes tend to be more sensitive) as well as the age of the person.

Visual comfort encompasses a variety of aspects, such as aesthetic quality, lighting ambiance and view. Usually the following aspects are considered to provide visual comfort:

- Views of outside space and connected to nature
- Light quality
- Luminosity
- Absence of glare

Working in a window-less office, even under adequate light conditions, and working in an office with a view, are totally different experiences. Abundant scientific studies show positive impacts of the latter on mood and job satisfaction, e.g. [28, 29, 30, 31, 32, 33].

Assessing a visual environment requires the analysis of three main factors – the sources of light (artificial/natural), the distribution of light within the space (colour, intensity) and its perception.

It is only recently that scientists have begun to understand how light influences our body and mind. Our perception of light is determined by the amount of radiation energy that enters the eye and the spectrum of this light. Knowing more about light and how to control it is crucial, as light directly influences our health and well-being, as well as our perception and experience of the surrounding environment.

Our personal history and culture also shape the way we appreciate light and visual environments. Extreme variations in preferred range of illuminance exist depending on age and culture. For instance, preferred light colours in Asia are quite different from those in Europe.

Until 20 years ago, most of the research on lighting was focused on how to provide enough artificial light to perform certain tasks. Since then, however, new demands for energy efficiency in buildings, as well as questions about the impact of artificial light on people's health, have led us to re-evaluate the benefits of natural daylight and re-consider the way we build for visual comfort.

Natural daylight is the illumination source to which our eyes are naturally adapted, so that we nearly always find it more comfortable than artificial lighting. When choosing a home, good natural light is often cited as an important criterion. In office environments, occupants have a preference for daylight and views, related to job-satisfaction and well-being. Daylight provides information about the hour of the day, the seasons, and the weather which helps to maintain our sense of psychological and social balance.

Office occupants with more light exposure during work hours sleep longer, and enjoy better sleep quality, more physical activity and a better quality of life compared with office workers with less light exposure in the workplace.

The availability of natural light varies constantly – depending on the geographical location, the season and time of day – so ensuring a continuous quality of light to provide optimal visual comfort is a sophisticated design challenge.

Building design and choice of materials and equipment obviously play a decisive role. Because natural light varies all the time, ensuring a constant quality of light involves controlling its intensity. This can mean either reducing too much incoming light by shading, or compensating for low light levels with artificial light. Increasingly sophisticated control systems are able to manage all these variables, and help achieve a successful balance in the combined use of artificial light and daylight. This will be shown during the course.

Parameters defining the visual comfort

Illuminance

Illuminance is the amount of light striking a surface – also known as incident light, where the “incident” is the light actually landing on the surface. Illuminance is calculated as the density of lumens per unit area and is expressed using lux (lumens/square meter). Illuminance is measure using a light meter. Figure 3 shows how to determine the illuminance over a horizontal surface.

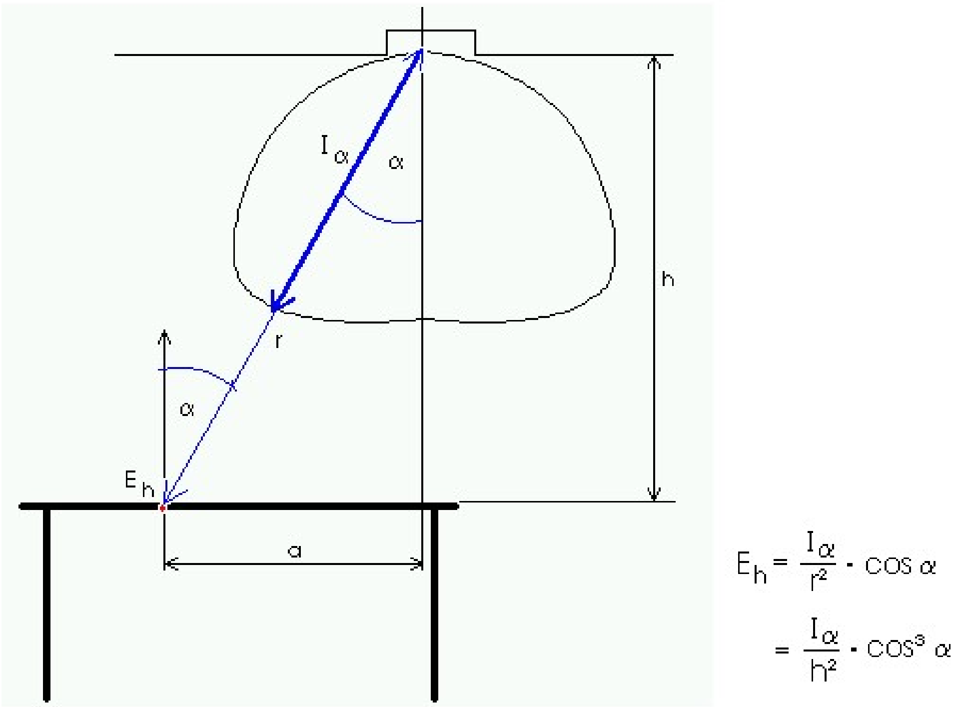


Figure 3. Determination of illuminance value over a certain surface [9].

Among the different papers in literature it has been decided to report an interesting result on a test room which allows to understand quickly the illuminance distribution in a room equipped with a wooden frame window with a total size of 2.0 m x 1.2 m and equipped with two conventional double low-emitting glazing filled with Argon. The two glasses have a size of 0.78 m x 0.90 m and are quite clear glasses. As can be seen form measurements during a clear sky day in June (Figure 4), the locations with the highest values of illuminance are the ones close to the external surface where the window is installed (points H3, H4 and H7). The natural illuminance decreases moving towards the most internal positions of the room.

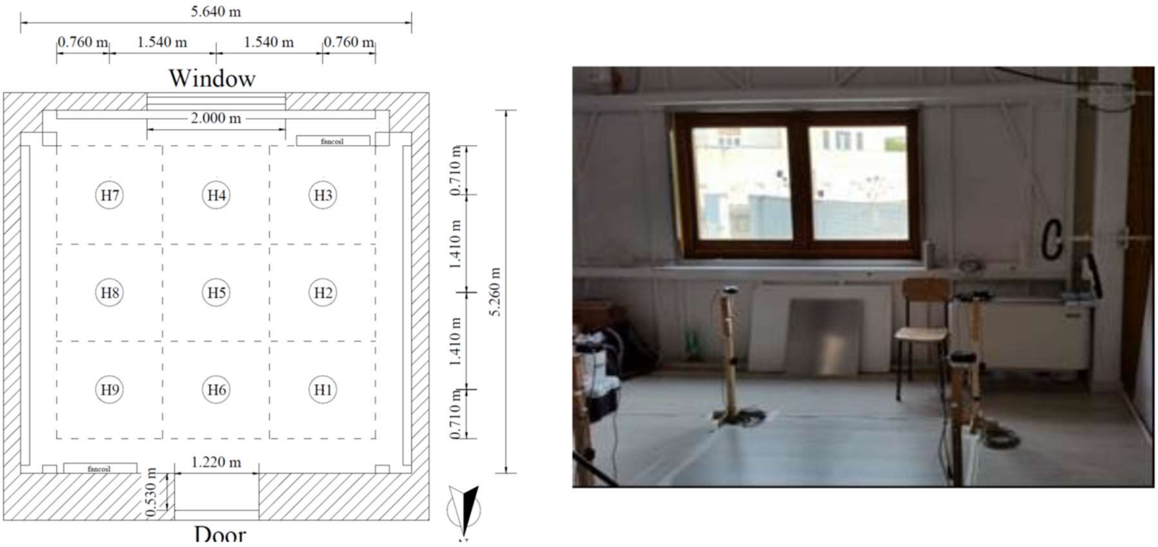


Figure 4. Layout of the experimental station as well as the position of illuminance-meters, from H1 to H9 (a), and the internal view of the station (b) [10]

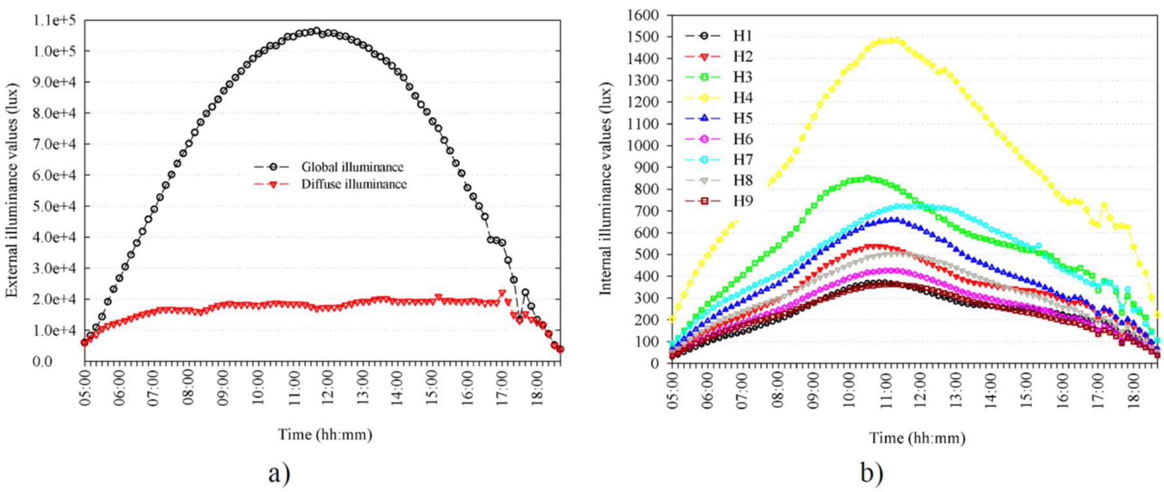


Figure 5. External diffuse and global horizontal illuminance values (a) and internal daylight illuminance values (b), both acquired on 18th June. [10]

The outdoor light level is approximately 10,000 lux on a clear day. In the building, in the area closest to windows, the light level may be reduced to approximately 1,000 lux, as shown in Figure 5. In the middle area it may be as low as 25 ÷ 50 lux. Additional lighting equipment is often necessary to compensate the low levels.

Earlier it was common with light levels in the range 100 ÷ 300 lux for normal activities. Today the light level is more common in the range 500 ÷ 1000 lux - depending on activity. For precision and detailed works, the light level may even approach 1500 ÷ 2000 lux. The table 1 is a guide for recommended light level in different workspaces, while in Table 2 other recommended light levels indoors are listed.

Table 1: Recommended light level in different workspaces [27]

Activity Illumination	**lux, lumen/m^2**
Public areas with dark surroundings	20 ÷ 50
Simple orientation for short visits	50 ÷ 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 ÷ 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 ÷ 5000
Performance of very prolonged and exacting visual tasks	5000 ÷ 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 ÷ 20000

Table 2: Additional recommended light levels indoors [27]

Office Space	
Normal work station space, open or closed offices	500
ADP Areas	500
Conference Rooms	300
Training Rooms	500
Internal Corridors	200
Auditoria	150÷200
Public Areas	
Entrance Lobbies, Atria	200
Elevator Lobbies, Public Corridors	200
Ped. Tunnels and Bridges	200
Stairwells	200
Support Spaces	
Toilets	200
Staff Locker Rooms	200
Storage Rooms, Janitors' Closets	200
Electrical Rooms, Generator Rooms	200
Mechanical Rooms	200
Communications Rooms	200
Maintenance Shops	200
Loading Docks	200
Trash Rooms	200
Specialty Areas	
Dining Areas	150÷200
Kitchens	500
Outleased Space	500
Physical Fitness Space	500
Child Care Centers	500
Structured Parking, General Space	50
Structured Parking, Intersections	100
Structured Parking, Entrances	500

Daylight factor (DF)

In architecture, a daylight factor (*DF*) [11] is the ratio of the light level inside a structure to the light level outside the structure. It is defined as:

$$DF = (E_i / E_o) \times 100 \qquad [\%] \qquad (1)$$

where E_i is the illuminance due to daylight at a point on the indoors working plane, E_o is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

To calculate E_i, requires knowing the amount of outside light received inside of a building. Light can reach a room through a glazed window, rooflight, or other aperture via three paths:

- Direct light from a patch of sky visible at the point considered, known as the Sky Component (*SC*),
- Light reflected from an exterior surface and then reaching the point considered, known as the Externally Reflected Component (*ERC*),
- Light entering through the window but reaching the point only after reflection from an internal surface, known as the Internally Reflected Component (*IRC*).

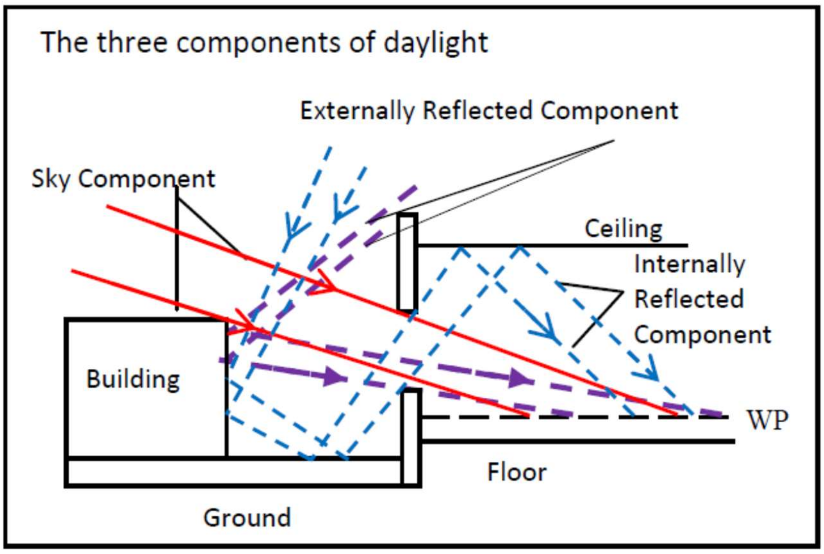


Figure 6. The three components of daylight: Sky Component (SC), Externally Reflected Component (ERC), Internally Reflected Component (IRC). [13]

The sum of the three components gives the illuminance level (typically measured in lux) at the point considered illuminance:

$$Illuminance = SC + ERC + IRC \qquad (2)$$

The daylight factor can be improved by increasing *SC*, for example placing a window so as to see more of the sky rather than adjacent buildings. The increase of *ERC* may be obtained by reflecting the light from surrounding buildings or objects (for example by painting surrounding buildings white). The increase of *IRC* may be carried out by using light colours for room surfaces. In most rooms, the ceiling and floor are a fixed colour, and much of the

walls are covered by furnishings. This gives less flexibility in changing the daylight factor by using different wall colours than might be expected [2] meaning changing *SC* is often the key to good daylight design.
Architects and engineers use daylight factors in architecture and building design to assess the internal natural lighting levels as perceived on working planes or surfaces. They use this information to determine if light is sufficient for occupants to carry out normal activities. The design day for daylight factor calculations is based on the standard CIE[2] overcast Sky for 21 September at 12:00 pm, and where the Ground Ambient light level is 11921 Lux.

Unified Glare Rating (UGR) and the other parameters defining glare

The Unified Glare Rating (*UGR*) helps to determine how likely a luminaire and its operation in a room are to cause discomfort to those around it, taking into account the eye level and direction of view of the user. The lower the value, the less discomfort the user will experience from the lighting.
A number of factors are considered when determining the *UGR* value: the measurement point, reflection factors and the location and operation of the lighting source. The UGR value considers all these factors. The lower the lighting discomfort or glare, the lower the value.
More in detail, the *UGR* can be calculated via the following equation:

$$UGR = 8\log\left[\frac{0.25}{L_b} * \sum \frac{L^2\omega}{\rho^2}\right] \qquad (3)$$

where L_b is the background luminance (cd/m^2), L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye (cd/m^2), ω is the solid angle of the luminous parts of each luminaire at the observer's eye (sr), ρ is the Guth position index for each luminaire (displacement from the line of sight).

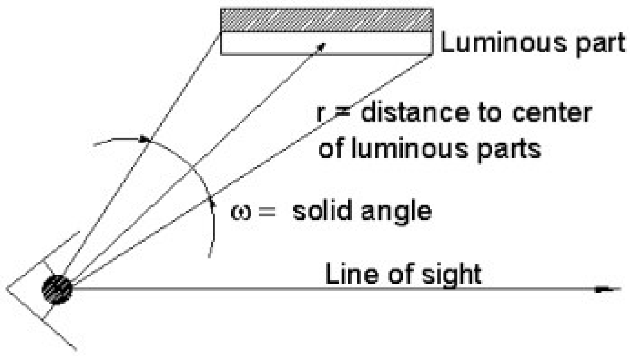


Figure 7. Explication of the parameters used for calculating the UGR [16]

The *UGR* classification includes five different quality classes, indicating the maximal *UGR* value which is permissible in particular spaces. In order to define a quality classification to

[2] CIE: International Commission on Illumination

be adopted as a minimum for different types of space, European standards have been formulated for this purpose. The *UGR* Limit values (*UGR-L*) values for a range of spaces are set out in the standard EN 12464-1 [14]. The following values apply for typical indoor spaces:

- Technical drawing UGR <16
- Offices UGR <19
- Reception areas UGR <22
- Archives, stairs and lifts UGR <25
- Corridors and passageways UGR <28

A luminaire with a *UGR* lower than 10 will create negligible glare.
More in detail, looking at correspondence between UGR and comfort perceptions, one UGR unit represents the least detectable step in discomfort glare evaluation, and 3 UGR units represent an acceptability step in glare criteria. Average UGR value range from 10-13-16-19-22-25-28. The relationship between calculated UGR value and Hopkinson's discomfort glare criteria is as shown in Table 3.

Table 3: Correspondence between UGR and Discomfort Glare Criterion

UGR	**Discomfort Glare Crtiterion**
10	Imperceptible
13	Just perceptible
16	Perceptible
19	Just acceptable
22	Unacceptable
25	Just uncomfortable
28	Uncomfortable

Another parameter which can be defined is the Visual Comfort Probability (*VCP*), which is a measure of discomfort glare for interior lighting applications. The visual comfort probability (VCP) is the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions. The table 4 shows this correlation.

Table 4: Correspondence between UGR and VCP

UGR	**Visual Comfort Probability (VCP)**
11.6	90%
16	80%
19	70%
21.6	60%
24	50%

Beside the VCP, other parameters can be defined, such as the DGI (Daylight Glare Index), the CGI (CIE Glare Index) and the DGP (Daylight Glare Probability). For more details you can see [17]. The relationship between the different parameters can be seen in Table 5.

Table 5: Correspondence between UGR and the other discomfort indexes

	imprecebtible	**perceptible**	**disturbing**	**Intolerable**
Unified Glare Rating (UGR)	<13	13 ÷ 22	22 ÷ 28	>28
CIE Glare Index (CGI)	<13	13 ÷ 22	22 ÷ 28	>28
Visual Comfort Probability (VCP)	80 ÷ 100	60 ÷ 80	40 ÷ 60	<40
Daylight Glare Index (DGI)	<18	18 ÷ 24	24 ÷ 31	>31
Daylight Glare Probability (DGP)	<0.30	0.30 ÷ 0.35	0.35 ÷ 0.40	>0.45

Another parameter which is used in lighting simulations is the Useful Daylight Illuminance (UDI) which is a modification of Daylight Autonomy conceived by Mardaljevic and Nabil in 2005 [34]. This metric bins hourly time values based upon three illumination ranges, 0÷100 lux, 100÷2000 lux, and over 2000 lux. It provides full credit only to values between 100 lux and 2,000 lux suggesting that horizontal illumination values outside of this range are not useful. There is significant debate regarding the selection of 2,000 lux as an "upper threshold" above which daylight is not wanted due to potential glare or overheating. There is little research to support the selection of 2,000 lux as an absolute upper threshold, although it is widely recognized that 2,500 lux is an excessive value, leading to glare.

Solar energy through windows

Solar radiation impinging a glazed surface can be transmitted, reflected or absorbed. Due to the energy conservation, the sum of the energy absorbed (I_a), reflected (I_r) and transmitted (I_t) is equal to the amount of incident energy (I):

$$I = I_t + I_a + I_r \tag{4}$$

Dividing by the overall energy impinging the surface, the following equation can be derived for the coefficients of sorption (α), transmission (τ) and reflection (ρ):

$$\tau + \alpha + \rho = 1 \tag{6}$$

The characteristics of a glazing element depend on the wavelength of the considered solar radiation. The absorption, transmission and reflection coefficients depend also on the angle of incidence of the solar radiation with respect to the normal incidence of the glazing surface (θ) [18], as reported in Figure 8.

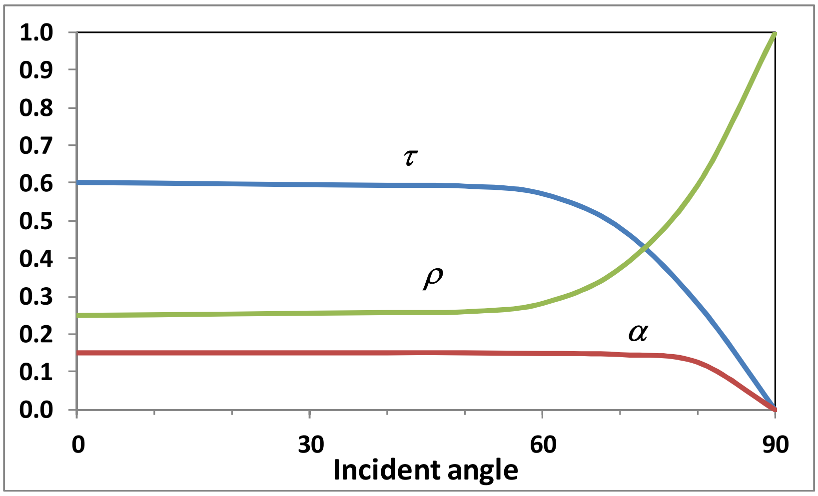


Figure 8: Transmission, sorption and reflection coefficients as a function of the incident angle

For obtaining the overall value of a coefficient (absorption, reflection or transmission), the incident radiation and the correspondent absorbed, reflected and transmitted radiation has to be integrated on the wavelength. For this purpose the incident angle has to maintained fixed, hence usually the values are provided for an incident radiation normal to the considered surface (θ=0°). As an example, the characteristics of the solar radiation transmittance is reported in Figure 9. The overall value of the generic coefficient M derives by the integration within the considered range [λ_1, λ_2] of the response $M(\lambda)$ of the glazed element with respect to the solicitation $P(\lambda)$:

$$M = \frac{\int_{\lambda_1}^{\lambda_2} M(\lambda)P(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} P(\lambda)d\lambda} \tag{7}$$

Solar energy through windows can be considered along the whole wavelength or only in the range of visible wavelength. The first case refers to the overall energy characteristics of the glazing surface with respect to the solar radiation (between 300 nm and 2500 nm), while the second case refers to the visual transmission through a glazed element (between 380 nm and 780 nm).

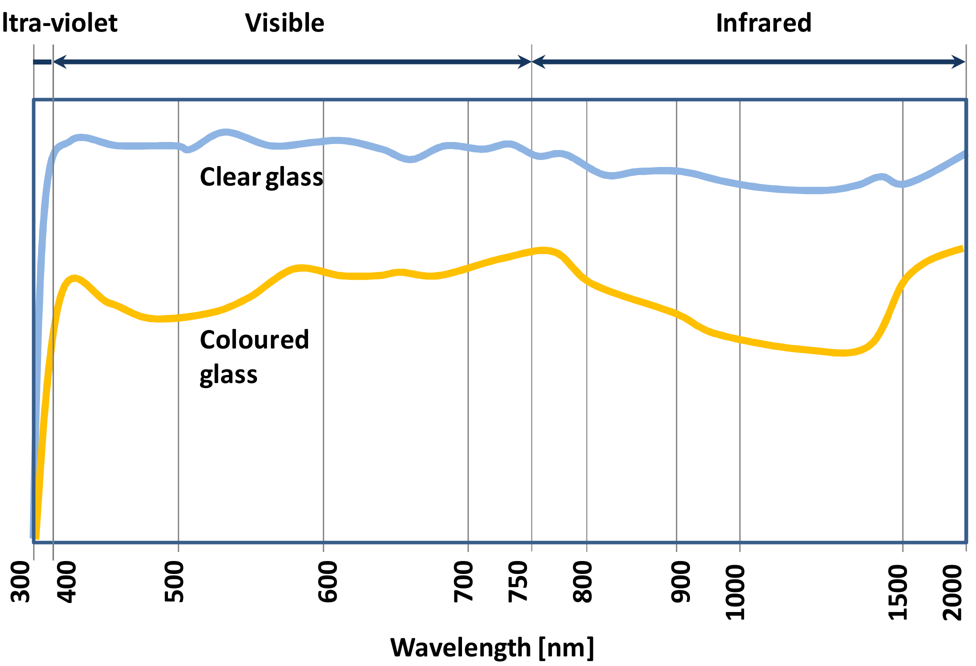


Figure 9: Transmittance characteristics of different glazing systems with respect to wavelength

Solar transmittance

Solar transmittance (τ_S) depends on the angle θ and on the wavelength λ. The intergal of the solar transmission over the whole wavelength range (between 200 nm and 2500 nm) is weighted on the curve of the energy intensity of a solar radiation with AM = 2:

$$\tau_S = \frac{\int_{300nm}^{2500nm} E(\lambda) \cdot \tau(\lambda, \theta) \cdot d\lambda}{\int_{300nm}^{2500nm} E(\lambda) d\lambda} \tag{8}$$

In figure 10, the different behaviours of some glazing elements are reported. As can be shown, a clear glass (float) permits a uniform transmission all over the wavelength. Glasses used in the past with colour bronze or grey limit the solar transmission in a uniform way along the whole wavelength. Glazing elements with selective behaviour allow transmission in the range of visible radiation, while they reduce the transmission in the infrared wavelength range (above 750 nm).

The solar transmittance alone can give an idea on the possible energy transmission through the glazing, but it does not represent the energy transmitted through the glazed element. In fact the solar radiation impinging a glazing system is reflected, absorbed and transmitted. The transmitted energy enters directly in the room, while the reflected energy does not affect thermal balance of the glazed surface. The absorbed radiation heats the glazing, therefore part of the energy enters the room via convection with the air and partly through infrared radiation with the other surfaces.

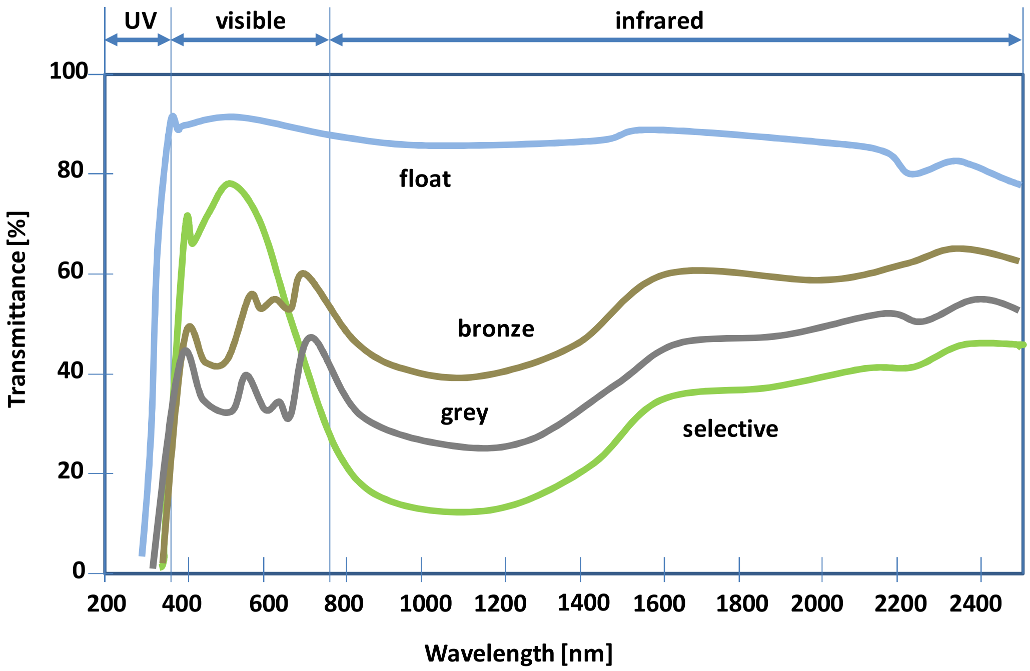


Figure 10: Transmittance characteristics of different glazing systems with respect to wavelength

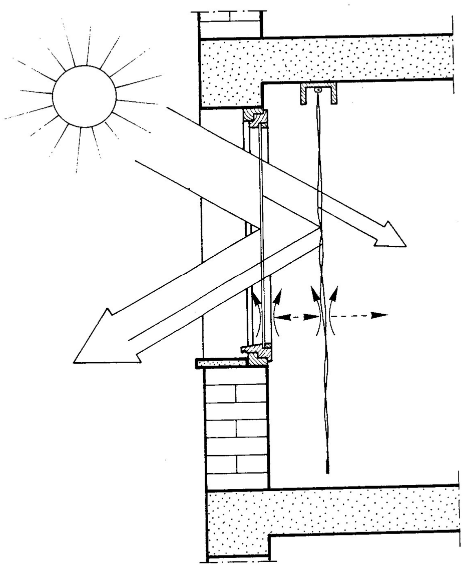


Figure 11: Thermal processes involved in the energy transmitted through a glazing surface [19]

This fact explains that this aspect is more complicated to be described than the solar transmittance. There are three ways to calculate the Solar Heat Gain (*SHG*):

1. Solar transmission through a reference clear glass panel
2. Solar transmission compared to the overall incident radiation
3. Detailed calculation within the elements which form the glazing system

Solar gain through a reference clear glass panel

The reference value of the solar transmission is usually estimated with a normal incident radiation. If the solar radiation impinges the glass with a different angle θ, the behaviour of the glass depends, among other factors, especially on the incident angle θ, as shown in Figure 8. For considering the behaviour of the energy transmitted through a generic glass for different incident angles, the simplest method compares the energy transmitted through the glass (I_{gl}) to the energy entering the room through a reference glazing surface ($I_{ref,gl}$), i.e. 3 mm float glass. The parameter defining the energy transmitted through the glass is called shading coefficient (C_s):

$$C_s = \frac{I_{gl}}{I_{ref,gl}} \tag{9}$$

This is the easiest way to calculate the solar heat gain. From a research investigation carried out in the 60ies [20] the following equation can be used for the k-th generic window:

$$I_{ref,gl,k} = I_{b,k}\left(B_{b,k} + A_{b,k}\right) + \left(I_{d,k} + I_{g,k}\right)\left(B_{d,k} + A_{d,k}\right) \tag{10}$$

where coefficients A_b, B_b, B_d and A_d depend on the solar incident angle θ as follows:

$$B_b = \sum_{j=1}^{6} b_j \left(\cos\theta\right)^{j-1} \tag{11}$$

$$A_b = 0.253 \cdot \sum_{j=1}^{6} a_j \left(\cos\theta\right)^{j-1} \tag{12}$$

$$B_d = 2 \cdot \sum_{j=1}^{6} \frac{b_j}{j+1} \tag{13}$$

$$A_d = 0.506 \cdot \sum_{j=1}^{6} \frac{a_j}{j+1} \tag{14}$$

The values for the coefficients a_j and b_j are listed in Table 6.

In this way, once calculated the energy transmitted through the reference glazing, by means of the shading coefficient C_s it is possible to estimate the energy entering the room through the actual glass. As an example, the solar thermal flux $I_{ref,gl}$, transmitted by the reference glass on 21 July at 42° N latitude (W/m^2) is reported in Table 7. In Table 8 an example of shading coefficients to be used in calculation is reported.

Once calculated the entering solar energy through each window in the considered time step ($I_{s,k}$), the overall solar gain can be determined as follows:

$$q_{s,k} = S_k C_{s,k} I_{ref,gl,k} \tag{15}$$

Table 6: Values of coefficients for determining the solar heat gain of a reference glass

j	b_j	a_j
1	-0.00885	0.01154
2	2.71235	0.77674
3	-0.62062	-3.94657
4	7.07329	8.57881
5	9.75995	-8.38135
6	-3.89922	3.01188

Table 7: Solar thermal flux $I_{ref,gl}$ transmitted by the reference glass on 21 July at 42° N latitude (W/m^2)

	Horizontal	South	West	North	East
6	84	38	38	109	369
7	257	76	76	104	593
8	440	106	106	106	650
9	595	172	129	129	604
10	717	262	147	147	481
11	795	331	158	158	295
12	824	359	162	162	164
13	805	341	257	159	159
14	737	279	446	150	150
15	623	191	584	133	133
16	474	115	648	111	111
17	296	83	616	110	83
18	116	47	435	115	47
19	3	2	29	12	2

Table 8: Shading coefficients for some glazing systems and shadings

	C_s [-]	U [W/(m^2 K)]
Single clear glass (3 mm)	1	6.33
Single clear glass + clear venecian blind (45°)	0.36	3.76
Single clear glass + dark venecian blind (45°)	0.50	3.76
Single clear glass + medium courtain	0.68	3.76
Double clear glazing	0.77	2.95
Double clear glazing + clear venecian blind (45°)	0.39	2.17
Double clear glazing + dark venecian blind (45°)	0.47	2.17
Double clear glazing + medium courtain	0.56	2.17
Double clear low emission glazing	0.55	1.85
Triple clear glazing	0.65	2.09

Solar gain compared to the overall incident radiation

The energy transmitted through a glass can also be defined considering, as reference, the impinging solar external radiation [21]. This parameter is called g-factor and it represents the sum of the transmitted energy through the glass and the fraction *c* of the energy absorbed by the glass which is transferred (via convection and infrared radiation) in the room (Figure 12) for a normal angle of incident radiation:

$$g = \frac{I_t + cI_a}{I} = \tau + c\alpha \qquad (16)$$

Since the reference glazing has g = 0.89, it is easy to demonstrate that the solar factor and the shading coefficient are linked via the following equation:

$$C_s = \frac{I_{gl}}{I_{gl,ref}} = \frac{g}{0.89} \qquad (17)$$

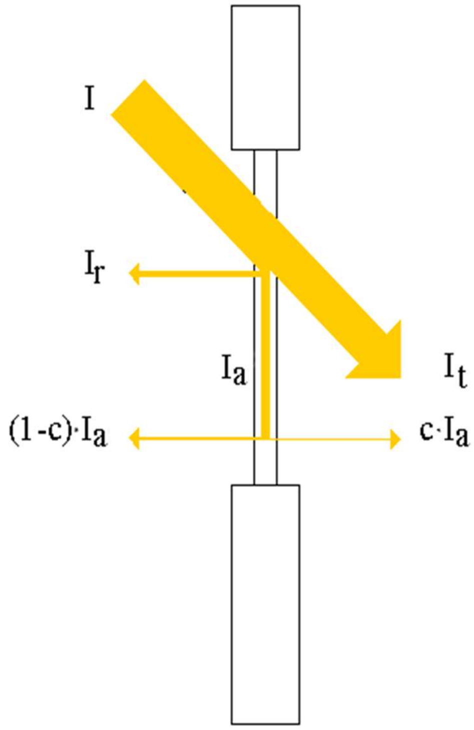


Figure 12: Determination of the g factor

In this case the solar energy entering the room is easy to determine for a generic angle of incidence by means of equation (10), changing equation (15) with the following equation:

$$q_{s,k} = \frac{S_k \cdot g_k \cdot I_{gl,ref,k}}{0.89} \qquad (19)$$

Detailed balance within the glazing elements

Solar heat gain is quite complex to estimate in a detailed way. The solar energy entering the room depends on the amount and characteristics of the glazing elements composing the window and on the presence of a shading device. The calculation is based on an iterative solution which tends to minimise the error of the solution [22, 23, 24]. Named *i* the generic glazing element, $I_1(i)$ is the radiation leaving the glass on the external surface and $I_2(i)$ is the radiation leaving the glass on the internal surface, which depend on the boundary conditions and on the characteristics of the considered glazed element (see Figure 13). The equations defining the absorbed and the leaving energy of the solar radiation on a glazing element can be defined through the following equations (Figure 13):

$$I_1(i) = I_1(i+1) \cdot \tau(i) + I_2(i-1) \cdot \rho_1(i) \tag{20}$$

$$I_2(i) = I_2(i-1) \cdot \tau(i) + I_1(i+1) \cdot \rho_2(i) \tag{21}$$

$$I_a(i) = I_1(i+1) + I_2(i-1) - I_1(i) - I_2(i) \tag{22}$$

Where $\tau(i)$ is the transmission coefficient, $\rho_1(i)$ is the reflection coefficient of the outer surface, $\rho_2(i)$ is the reflection coefficient of the inner surface $I_a(i)$ is the absorbed radiation. Applying the equations (20), (21) and (22) to all the glazing surfaces of the window, the solar radiation transmitted into the room is defined. Moreover the absorbed radiation $I_a(i)$ in each glazing element is defined and is then considered in the thermal balance of the glazing elements. The generic glazing element can be transparent or a shading device with suitable values of absorption, transmission and reflection coefficients to be used in equations (20), (21) and (22).

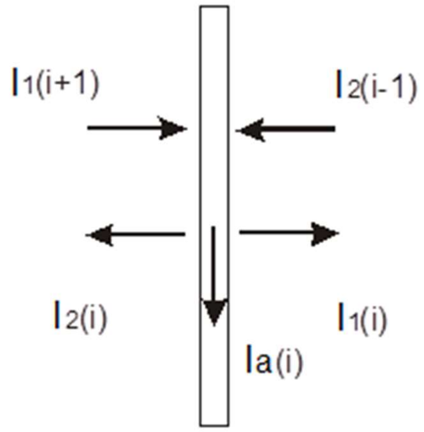


Figure 13: Radiation processes in a general i-th glazing element

The general scheme for the thermal balance inside a window is defined byu means of a resistance network, where conduction through glazing elements, convection and infrared radiation in cavities are considered (Fig. 14.a). For the generic *i*-th element, defined 1 and 2 the inner and outer surface respectively, the following equation can be written:

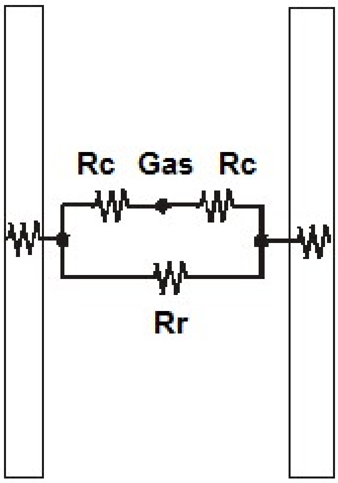
$$\begin{aligned} & S \frac{4\sigma_n T_m^3}{\left(\dfrac{1}{\varepsilon_{1(i+1)} + \varepsilon_{2(i)} - 1}\right)} \left(t_{1(i+1)} - t_{2(i)}\right) + S \frac{\lambda_i}{s_i} \left(t_{1(i)} - t_{2(i)}\right) + \\ & + S h_c \left(t_{a(j)} - t_{2(i)}\right) = S \frac{I_a(i)}{2} \end{aligned} \tag{23}$$

where a_j is the *j*-th air cavity between elements *i* and *i*+1.

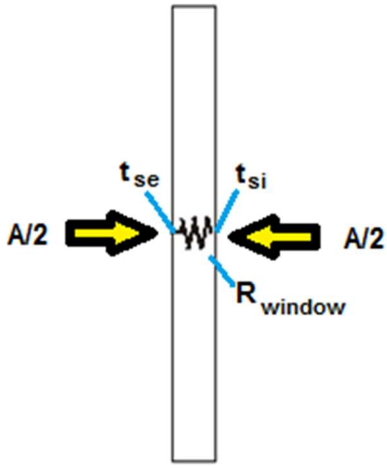
With this model the solar gain entering the room is the overall transmitted radiation ($\tau_{tot,k}$), i.e. the transmitted radiation by the most internal glazing element of the *k*-th window. The part of the absorbed radiation which is transferred into the room via convection with air and infrared radiation with all the other surfaces is already included in the model and solved internally by means of the set of equations (23) for each *k*-th window. Therefore with this method, the solar radiation to be considered impinging the room surfaces is:

$$q_{s,k} = S_k(\tau_{Dtot,k} I_{D,k} + \tau_{dtot,k} I_{d,k} + \tau_{gtot,k} I_{g,k}) \tag{24}$$

Usually the directions of the direct, diffuse and reflected solar radiations differ, hence in the model the mutual reflections, absorptions and transmissions have to be separated for considering the different behaviour with respect to incident angles of the glazing elements. This means that equations (20), (21) and (22) should be calculated separately for the direct, diffuse and reflected incident radiations.
A simplest version of the model can be carried out by means of the overall resistance of the window R_{window} (without overall heat exchange coefficients with the indoor and outdoor environments), together with its overall absorption, transmission and reflection coefficients (Figure 14.b). In this way, the overall absorption solar radiation can be split in two, hence it is included in the external and internal surface equations, as will be shown during the course.



a



b

Figure 14: Possible schemes for determining window thermal balance

Visual transmittance

Visual transmittance (τ_V) is estimated not only by means of the optical properties of the glazed element, but also by means of the effect that the visible component of the solar radiation (380-780 nm) has on human eyes. Human vision sensibility depends on the spectrum of solar radiation; as a matter of fact the peak of sensitivity of human eyes is related to 480 nm (colour blue), as shown in Figure 15. The function describing the sensitivity of the human eye to the visible radiation is called $V(\lambda)$. The visual transmittance can be thus estimated as:

$$\tau_S = \frac{\int_{300nm}^{780nm} I(\lambda)\cdot V(\lambda)\cdot \tau(\lambda,\theta)\cdot d\lambda}{\int_{300nm}^{780nm} I(\lambda)\cdot V(\lambda)\cdot d\lambda} \tag{25}$$

In practice, visual transmittance is estimated by means of the response of two filters, i.e. the glazed element and the human eye, and it represents already the effective perceived visible solar radiation passing through the considered glazing surface for a normal incident radiation.

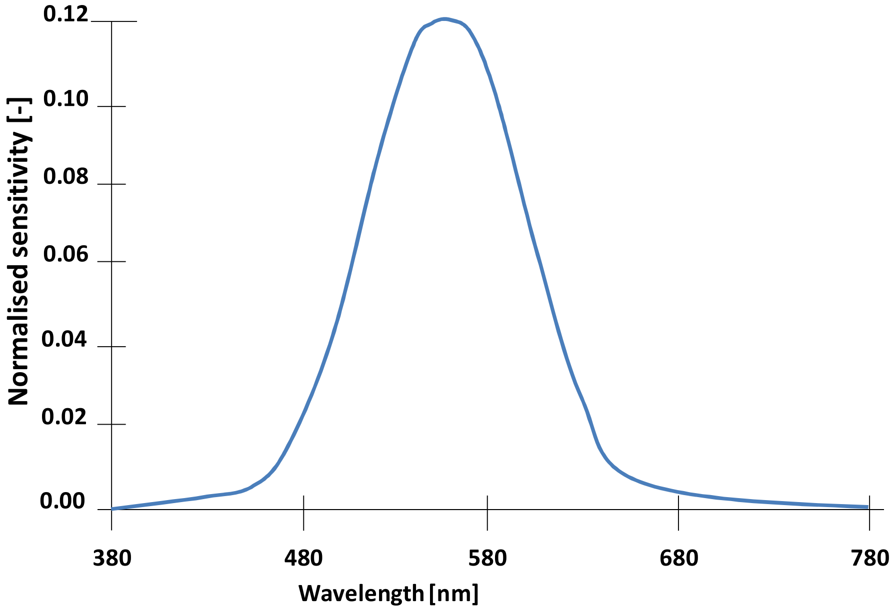


Figure 15: Response of human eye to the visible solar radiation spectrum

As an example, to resume all the energy characteristics of a glass, in Table 9 are reported the main parameters which define the overall thermal performance of a window, i.e. U_g, τ_v and g.
An interesting picture is reported in Figure 16 where the visual transmittance tv is reported on the horizontal axis and the solar heat gain coefficient in the vertical axis. As can be seen, for non-selective glasses these two parameters are similar, due to the fact that the transmission curves are quite flat all over the wavelengths. For selective glasses (i.e. glasses with low g-values) there is a ratio of around 2 between the solar transmittance τ_v and the solar heat gain coefficient *SHGC*. This is very important to allow daylighting and at the same time to reduce the risk of overheating. In any case, it is always recommended to install shadings (internal or external).

Table 9: Resume of overall energy performance of windows coefficients for some glazing systems

Description	**U-value W/(m² K)**	**τ_v light(%)**	**g-value (%)**
Single clear glass (4mm)	6.0	91	89
4-12-4 mm (Air)	3.0	80	68
4-12-4 mm (Argon and low-emissivity)	1.5	77	58
4-12-4-12-4 (Air)	2.0	72	59
4-12-4-12-4 (Air and low-emissivity)	1.2	77	55
4-12-4-12-4 (Argon and low-emissivity)	0.5	70	45
4-12-4 mm (Air, medium reflective and low-emissivity)	1.6	29	30
4-12-4 mm (Argon, medium reflective and low-emissivity)	1.6	9	18

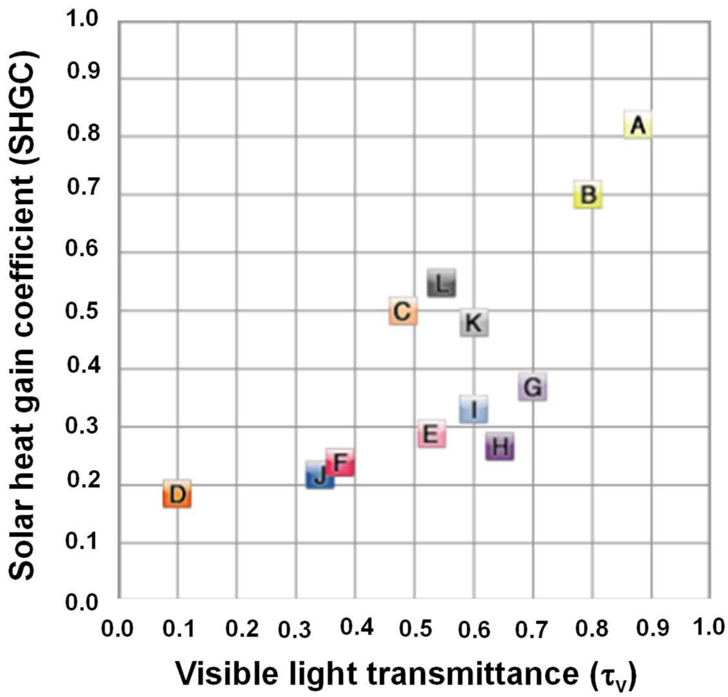


Figure 16: Visible light transmittance Vs. solar heat gain coefficient [25]

An example of overheating and visual discomfort in an office building

As a final example, to show the effect of too high solar radiation in terms of entering energy (high *SHGC*) and too much light (too high τ_v) a detailed analysis of a retrofit solution for a

glazed building is shown [26]. The purpose is not to propose the film coating as standard solution, but to show the effects on comfort and energy related to the choices of glass energy performance.
The building selected was the MG Tower (Figure 17). It is a nine-storey building located in the industrial area of Padua, Italy (site characteristics enable the building to receive direct radiation without being sheltered or shaded by other surrounding buildings). This building was chosen as it was recently constructed (2007), is relatively well documented and it is designed with South, West and East facing fully glazed façades. The building consists of two architectural elements: a slightly flared cone (hereinafter, it will be referred to as to the "Cone") which rises from the first floor to the eighth and a squared parallelepiped (hereinafter, it will be referred to as to the "Parallelepiped") which is nine floors in extent.

a

b

Figure 17: Pictures of the building which has been investigated

Despite the existence of a modern glazing system with solar control properties, the glazed façades proved to perform poorly. After the building was first occupied, the majority of complaints were related to thermal comfort; occupants' perception was that indoor temperatures were unconformable. Occupants repeatedly claimed they were excessively hot during sunny days throughout most of the months of the year. To provide a remedial solution, the building owner agreed to the application of a solar control film to all the glazed surfaces of the Parallelepiped, with these surfaces being East, South and West oriented (Figure 18). Prior to the application, a window film was selected with performance capable of rectifying the identified heat gain and glare problems associated with the existing glazing. The most significant properties of the film which was selected as the most suitable for the described intervention (are listed in Table 10).
The key periods of the investigation are summarised as follows:

- The monitoring of the selected building started during the second half of May 2009; film was not installed;
- Film installation commenced from the end of June 2009; most of film installation took place during July 2009; eventually, film application ended by August 2009;
- The monitoring of the demonstration building lasted until the end of September 2010.

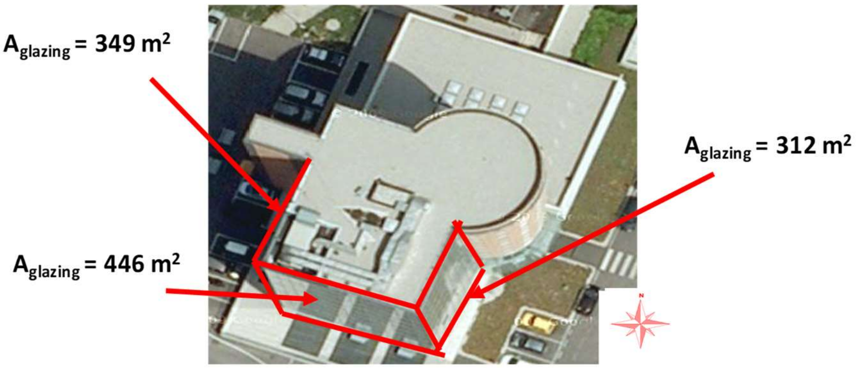


Figure 18 – Pictures of the building which has been investigated

Table 10: Glazing characteristics before and after intervention

Condition	g-value	Total solar energy rejection	Visible light transmittance	Glare reduction	Thermal transmittance
Pre intervention glazing	0.43	57 %	τ_v = 59.3 %	33 %	U = 1.2 W m^{-2} K^{-1}
Post intervention glazing	0.15	85 %	τ_v = 13.6 %	85 %	U = 1.2 W m^{-2} K^{-1}

Thermal comfort measurements

Some of the results are resumed in Table 11. Although summer conditions in 2009 and 2010 were slightly different, it can be concluded that overheating periods were much higher in year 2009 before the film was installed. It should be noted that before film application the monitored air temperature on a number of occasions exceeded the higher limit of 30°C whilst, after film application, indoor air temperature remained al-ways below that level. The internal thermal environment was significantly affected by the outside conditions especially on weekends, when HVAC operation was usually reduced; undoubtedly, the effect of the solar control film helped to reduce indoor temperature fluctuations in response to external temperature changes and solar irradiation. Before film was installed, on weekends the negative impact of solar penetration was emphasised; solar gains used to raise indoor temperatures up to 35°/40°C on weekends as there was usually no air conditioning to counteract the increase due to solar heat gain.

Table 11: Indoor temperature intervals occurrences with reference to July and August 2009 (film installation not completed) vs July and Augiust 2010 (film installation completed)

Category [°C]	**Percentage of total occurrences**					
	July 2009 vs July 2010			**August 2009 vs August 2010**		
	Before	**After**	**Change**	**Before**	**After**	**Change**
< 24	0 %	0 %	+ 0%	0 %	2 %	+ 2%
≥ 24 and < 26	6 %	32 %	+26 %	10 %	46 %	+37 %
≥ 26 and < 28	44 %	53 %	+10 %	59 %	49 %	-10 %
≥ 28 and < 30	38 %	15 %	-23 %	24 %	3 %	-21 %
> 30	12 %	0 %	-12 %	7 %	0 %	-7 %

Visual comfort measurements

A comparison on indoor illuminances on the horizontal plane has been carried out. As an example, for the 4th floor office as recorded from 8 July 2009 to 15 July 2009 (Figure 19.a, film not installed) and from 9 September 2009 to 15 September 2009 (Figure 19.b, film installation completed). Below the graphics of illuminance levels, the solar radiation in the two selected weeks is also reported. It must be noted that the two weeks were comparable with respect to available solar radiation, with the exception of 14 September 2009. The effect of solar control window film for reducing potential disturbance within the indoor visual environment can be easily understood, as recorded maximum values before film installation was completed, including those values exceeding the limit of 4000 lux, were considerably lowered after film installation. Even if it is acknowledged that discomfort glare is not to be assessed by means of horizontal work plane illuminance because the amount of light falling on a working area lacks information about overall personal visual experience of a room, high values of horizontal illuminance provide direct evidence of potential visual discomfort.

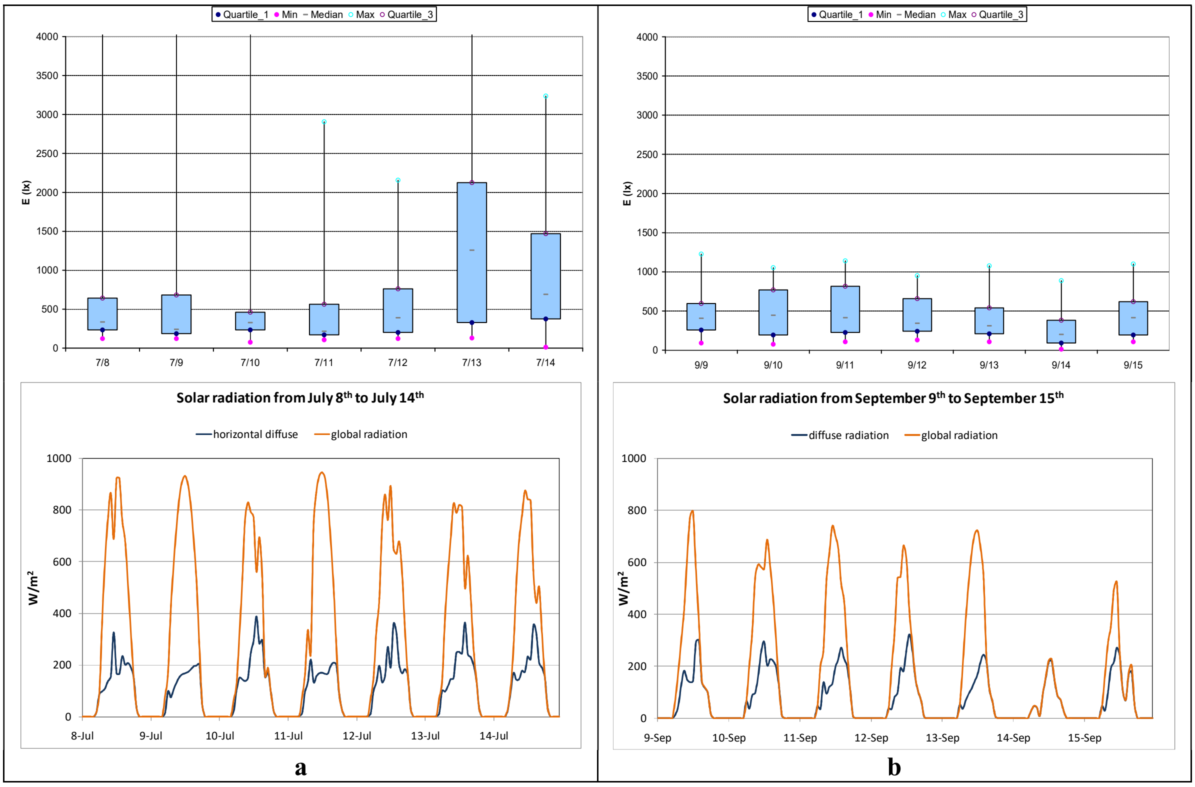


Figure 19: Comparison of illuminance values before (a) and after (b) film installation with the solar radiation for the considered periods

In addition, the luminance distribution at the subjects' workstations was measured using High Dynamic Range (HDR) imaging, which is acknowledged as an innovative approach to the evaluation of luminance values [35]. The HDR picture contains the dynamic range of luminance conditions in a scene similar to that which the human eye can see. The HDR technique consists in taking multiple exposure photographs of static scenes using a digital camera with a fisheye lens to capture a se-quence of images at different exposures.
Moreover, it is very important to note that window film enabled the view to the outside (Figure 4.c and Figure 4.d); preventing a view to the outside was identified by this research as being a cause of major discomfort. As a matter of fact, it is impossible to distinguish

the features of the nearby buildings when film is not installed and blinds are retracted, compared to a good view after film installation.

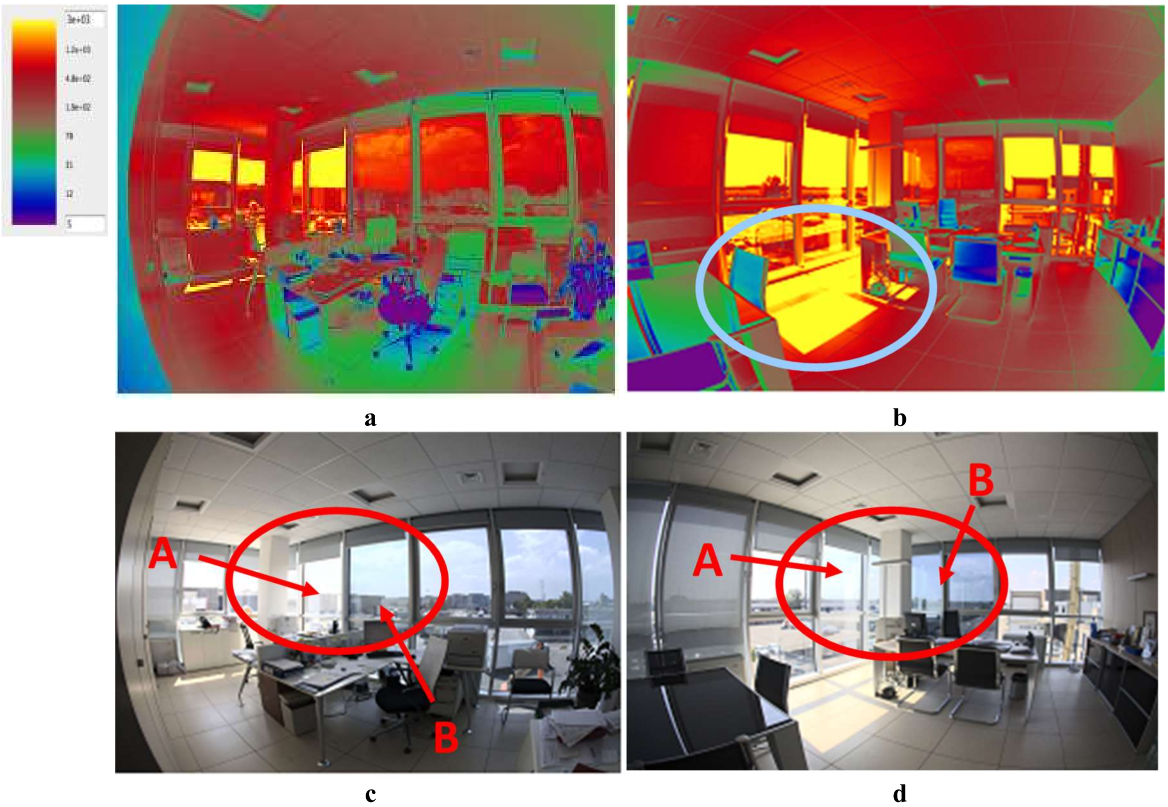


Figure 20: DR images of two offices taken during film application and false colour image which maps the luminance distribution within two rooms (a) and (b). Differences in the view to the outside resulting from film installation (c) and (d): "A" points existing glazing; "B" points filmed glazing

Subjective evaluation by occupants

A questionnaire was used to evaluate occupants response to the energy saving intervention due to film application [36]. The questionnaire used allowed a statistical evaluation of subjective answers that provide diagnostic information expressed by ordinary users as regards the thermal environment around them. Occupant surveys are a valuable source of information for improving the knowledge of how buildings are performing and how occupants interact with the building.
The survey was used to conduct pre and post intervention assessments of occupant comfort in the monitored building. The baseline survey was conducted during June 2009. To control for seasonal variation and to characterize a possible temporal variability of subjects experience, as well as to prevent any influence inherent in the "newness" of the surroundings, two separate post intervention surveys were conducted. The first post-intervention survey took place almost exactly after the intervention had occurred (September 2009); the subsequent survey took place between February and March 2010 (this waiting period allowed occupants to become accustomed to their new working environment in order that the experience of change itself does not bias results.). Detailed physical measurements (air temperature, mean radiant temperature, air velocity, relative humidity) of environmental parameters affecting thermal comfort were recorded at each respondent's workstation. All occupants of the building were invited to participate once over a four-week period, and the mean response rate was approximately 57%. Some of the results of the surveys are reported in Figure 21.

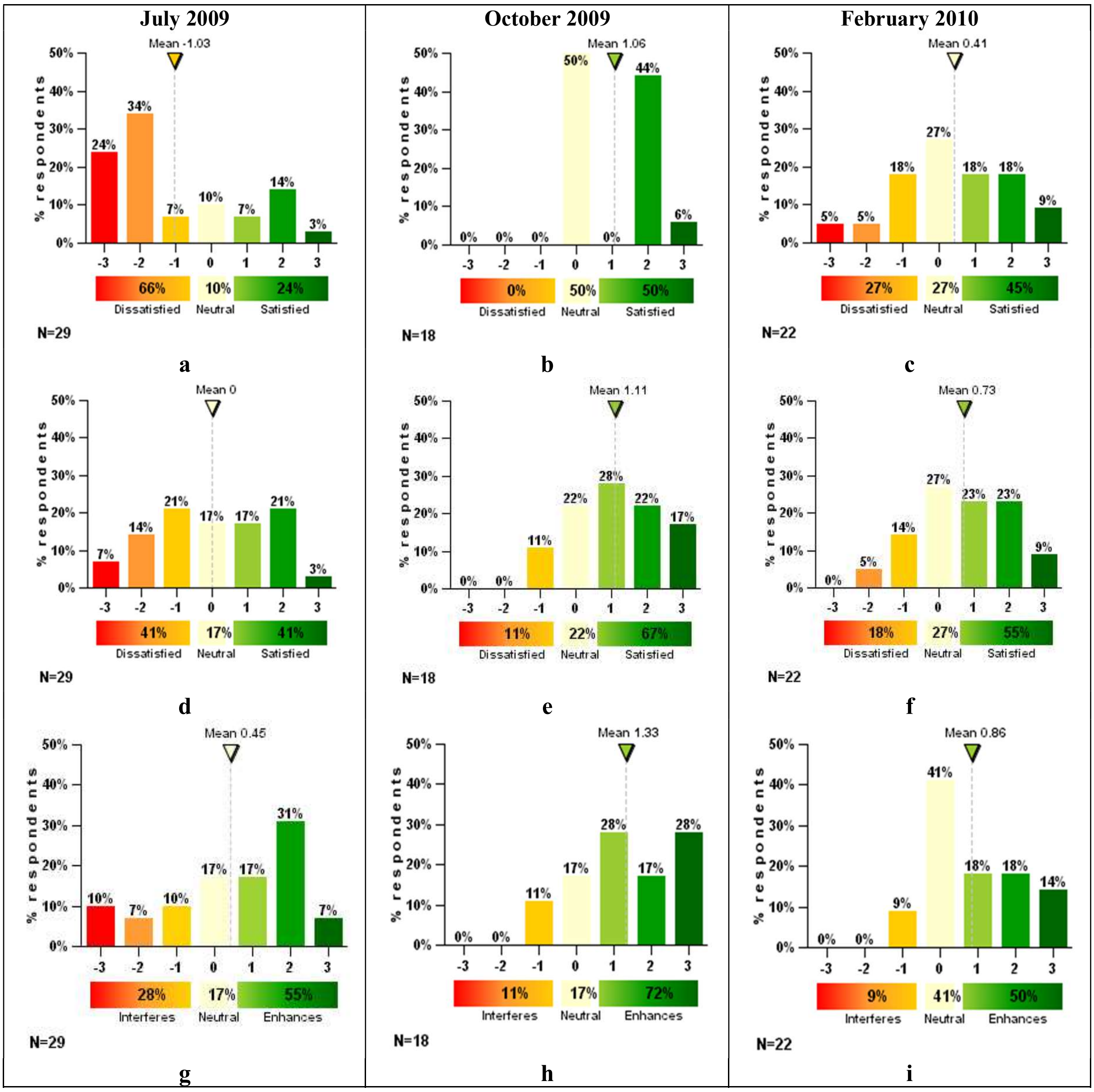


Figure 21 – Level of satisfaction about the experienced thermal environment (a, b, c), level of satisfaction about the visual comfort of the lighting (d, e, f), self reported influence of the indoor visual environment on the ability of performing a task (g, h, i).

The distributions of thermal comfort satisfaction scores (Figures 21.a, 21.b, 21.c) demonstrates clearly that occupant satisfaction not only increased post-intervention, but improved satisfaction was maintained over a considerable period of time. Those occupants who expressed dissatisfaction with the temperature in their workspace were asked to identify a possible cause; as could be expected, occupants identified the primary cause of their discomfort in the heat gain surplus due to sun penetration through the glazing within the building.

The survey was also intended to examine occupants' perception of their visual environment and to see whether they identified related problems. In more detail, occupants were also asked if they were satisfied with the visual comfort the lighting provided (Figures 21.d, 21.e, 21.f). The second and the third surveys for post-installation of window film showed that there was a significant rise in the satisfaction with the level of lighting when investigating phenomena such as contrast, glare and reflections.

In the results shown in Figures 21.g, 21.h, 21.i it can be noted how the 10 % (i.e. the dark red histogram in the leftmost picture) of respondents which were totally unsatisfied with their visual environment before films were applied changed their mind after films were installed. This analysis of the perceived visual environment provides good evidence that the solar control window film used does not affect detrimentally workers' experience of internal light levels after film installation but, on the contrary, film installation actually enhances the workers' visual environment.

Simulations and lighting analysis

The lighting analysis has been carried out with both RADIANCE [37] and DAYSIM [38]. The validation of the lighting model shows that DAYSIM predictions can be used to represent real illuminances; it follows that, although it was not possible to monitor illuminance values before film installation, all the considerations regarding the visual conditions (glare occurrence, operation of blinds) in the case film was not installed are completely plausible. Monthly Useful Daylight Illuminance (UDI) ranges for two selected offices (a double office and a single one) were calculated based on the illuminance profiles obtained by DAYSIM. The pre-intervention status was compared to the "with film" conditions, taking into account both shading up and down conditions, to show the yearly occurrence of low, adequate and excessive (glare) lighting levels with reference to all of the occupancy hours for year 2009. As regards the double office considered in the analysis, that is South-East oriented, considering the glazing without film condition, glare is likely to occur every month of the year, and sometimes (February and March) even in the case blinds are down (Figure 22.a). In fact without shading, UDI2500 which definitely corresponds to glare occurrence, varies from 14% of the hours to 66% (Figure 22.b) in the pre-intervention status, while, in the case film are installed, glare is likely to occur only in February and March (although to a very limited extent, as the maximum is 8% of the time, which is better than if blinds alone are used,). Considering a single office with two glazed façades, one South-East and one South-West exposed, UDI2500 values are considerably higher than the double office room (e.g. in July as well as in August, UDI2500 represents excessive glare for 96 % of the working time, as shown in Figure 22.d). In wintertime (Figure 22.c), films may cause reduced lighting levels; nevertheless, from occupants interviews, it emerged that before film application, they often had to keep blinds down to prevent reflections on the screens and, consequently, they were forced to switch on the lights. Considering visual comfort, it is important to note that traditional shadings such as curtains or blinds, if operated, do not allow the view out, which, if precluded, is considered one of the main sources of dissatisfaction.
The electric energy consumption of each floor of the tower before and after film installation, were assessed. By comparing electricity bills, it emerged that there is no un-equivocal evidence for increased energy use after film is installed.

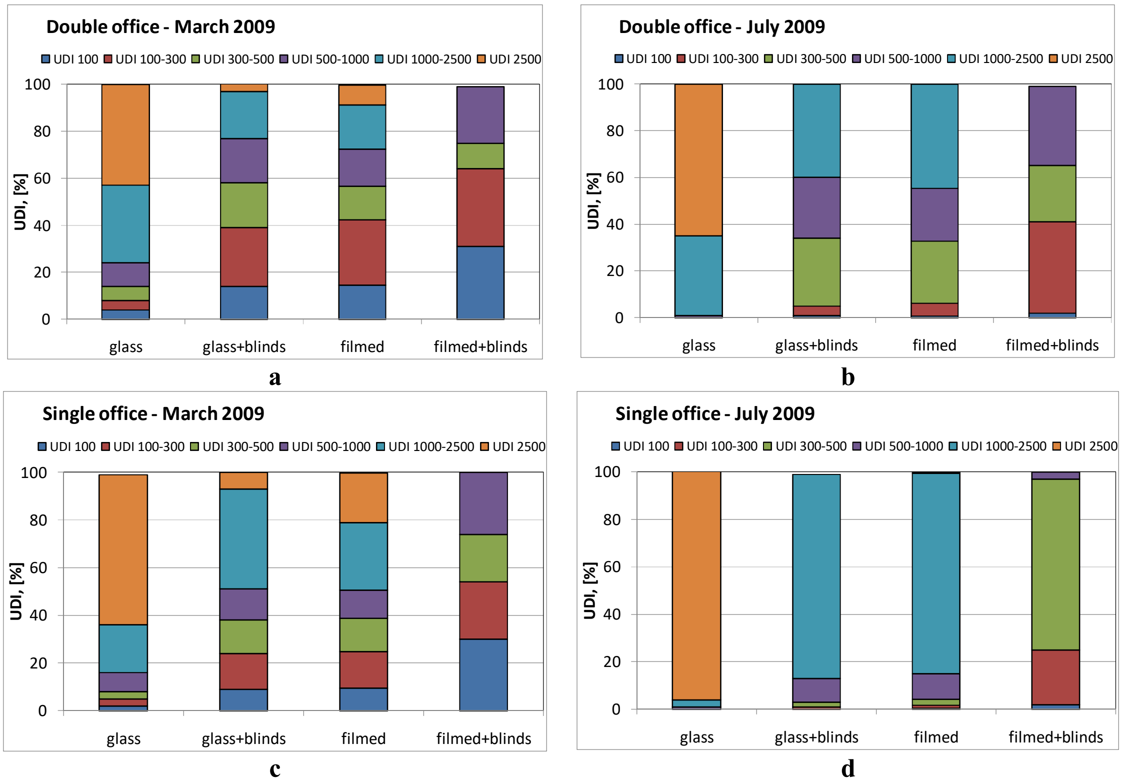


Figure 22 – UDI ranges, calculated for the year 2009, considering the situations for pre- and post-installation of the window film, for both roller blinds up and down conditions in a double office in March (a) and July (b) and in a single office in March (c) and July (d). Note that the orange colour indicates glare conditions

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