Transparent Building Envelope: Windows and Shading Devices Typologies for Energy Efficiency Refurbishments

G. Cellai, C. Carletti, F. Sciurpi and S. Secchi

Abstract Main typologies of windows, typical of the existing buildings, and innovative solutions, special glasses, and shading devices (fixed shading, mobile shading, roller blinds, and curtains) are described and assessed. The windows and solar shadings' appropriate choices are evaluated on the basis of a case study. For each of these solutions, thermal efficiency, natural lighting, and acoustic performances have been assessed with appropriate calculation codes. Dynamic computational methods with a graphical interface are used (EnergyPlus, through the Design Builder interface, for energy simulations, RELUX to simulate natural lighting, and DISIA for the acoustic simulations). Four representative climatic datasets corresponding to various locations (Berlin, Milan, Florence, and Athens) were considered. Appropriate performance indicators (defined by regulations or conventionally applied in science) have been identified in order to analyze performances and to evaluate different strategies for the achievements of energy efficiency and of comfortable environments: Q_{sw} (winter solar gains), θ_o (operative temperature), F_w (reduction factor of winter solar gains), DF (average daylight factor), UDI (useful daylight illuminance), daylight uniformity, $D_{2m,\ nTw}$ (acoustic insulation of facade normalized with respect to the reverberation time), and Δl_{fs} (sound pressure level difference due the façade shape). Starting from the performance evaluation of existing buildings, according to a logic implementation of consequential performance, this study provides for the assessment of different phases: the first interventions (phase A), replacement of existing windows with

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A. Magrini (ed.), *Building Refurbishment for Energy Performance*,
Green Energy and Technology, DOI: 10.1007/978-3-319-03074-6_2,

other high-energy performance ones (phase B), adaptation of the thermal transmittance of opaque envelope to national limits (phase C), and introduction to solar systems and solar control glasses (phase D). Then, the effect of screens and windows on the reduction in the thermal loads in the summer season and on the thermal comfort has been assessed, together with the influence on visual and acoustic comfort of different configurations of windows and shielding. Finally, a comprehensive evaluation on the aspects of energy consumption, natural lighting, acoustic comfort, and technical feasibility (TF) is carried out.

Symbols

A	Area (m^2)
A_g, A_f	Glass and frame area (m^2)
$D_{2m,nTw}$	Standardized façade sound level difference (dB)
DF	Daylight factor (%)
E	East orientation
E_{int}, E_{ext}	Indoor and outdoor illuminances (lux)
$E_{\mathrm{min}}/E_{\mathrm{m}}$	Daylight uniformity (–)
g	Solar factor (%)
I_{sol}	Solar radiation (W/m^2)
N	North orientation
Qs_w	Winter solar gains (kWh)
Qs_s	Summer solar gains (kWh)
θ_{o}	Operative temperature (°C)
F_w	Reduction factor of winter solar gains (%)
F_s	Reduction factor of summer solar gains (%)
Ra	Color-rendering index (–)
R_w	Rating of sound reduction index (dB)
S	South orientation
SC	Shading coefficient (%)
U	Thermal transmittance [W/(m^2 K)]
UDI	Useful daylight illuminance (–)
U_g	Thermal transmittance of the glass [W/(m^2 K)]
U_f	Thermal transmittance of the frame [W/(m^2 K)]
U_w	Thermal transmittance of the window [W/(m^2 K)]
l_g	Total perimeter of the glazing (m)
Ψ	Linear thermal transmittance [W/(m K)]
W	West orientation
Y_{IE}	Periodic thermal transmittance [W/(m^2 K)]
ΔL_{fs}	Façade shape level difference (dB)
φ	Phase shift
Ψ_g	Linear thermal transmittance of glass [W/(m K)]
α	Noise absorption coefficient (–)
λ	Thermal conductivity [W/(m K)]
θ_{db}	Dry bulb temperature (°C)

τ_v Light transmittance (%)
τ_λ Spectral light transmittance (%)

1 Generalities

The relation between window openings and outdoor calls for three specific needs:

1. heat flow control through components with a low thermal inertia capacity;
2. protection from solar radiation;
3. visual connection between the envelope and the outside and therefore a satisfactory level of natural light.

The first requirement, strictly related to energy efficiency, has pushed forward the development of material components with low transmittance values (thermal transmittance value U_W): their improved performances are producing positive outcomes in terms of thermal and acoustic comfort.

The second requirement deals with the light control through the glass panes (with total solar transmittance g value and light transmittance τ_v) and with the application of screen devices to protect against solar radiation and to ensure occupants' comfort.

The third need is prominently centered on the visual comfort (VC) demand.

The replacement of windows, aimed to energy refurbishment, represents the kind of intervention that brings the most efficient cost/performance ratio, often promoted by tax incentives; this kind of solution is also practicable by simply substituting the existing glazing with new ones, maintaining the same frame.

2 The Thermal Performance

Three components define the thermal transmittance of a window (U_W): the glass panes, the frame (fixed or operable), and the spacer between panes (multiglazed windows).

The following heat exchange process combinations must be taken into account (Fig. 1):

- Convective and radiative heat transfer between the outer and the inner adjacent surfaces;
- Conductive, convective, and radiative heat transfer within the cavities of the window itself (double-glazed or double-framed windows).

The thermal transmittance value can be calculated as follows [27]:

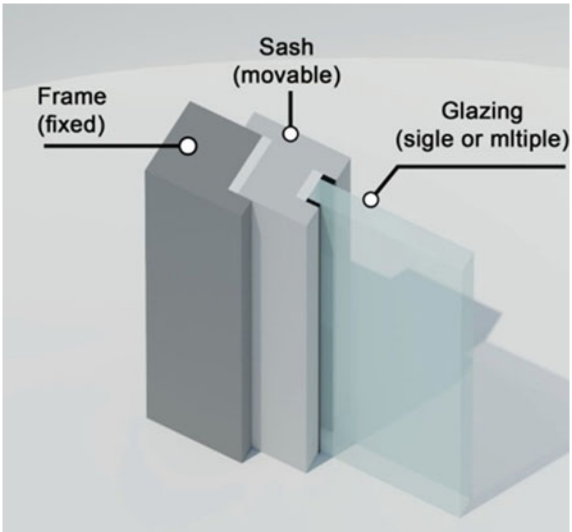


Fig. 1 Single window scheme

$$U_W = \left(A_g U_g + A_f U_f + \Psi_g l_g\right) / \left(A_g + A_f\right) \left[\mathrm{W}/(\mathrm{m}^2\,\mathrm{K})\right] \quad (1)$$

where

U_g	Thermal transmittance of the glass [W/(m^2 K)]
U_f	Thermal transmittance of the frame [W/(m^2 K)]
A_g, A_f	Glass and frame area (m^2)
l_g	Perimeter of visible glass edge (m)
Ψ_g	Linear thermal transmittance due to the combined thermal effects of glazing, spacer, and frame [W/(m K)]

For a conservative approach, the computation of U_W is proceeded under the common practice of neglecting the shield film layer, if present, handling it as inactive (this does not apply, however, to the procedure of irradiance considering solar gain calculation).

For double-glazing panes bonded around the perimeter of the spacers, the cavity holding air, performing a low value of thermal conductivity ($\lambda \cong 0.025$ W/(m K)), plays a decisive contribution in terms of thermal resistance improvement.

Further on, the reduction in conductive and convective heat transfer is possible, thanks to the development of several solutions, such as in Fig. 2:

- the application of gas layer with a thermal conductivity lower than the air conductivity (for instance, argon and krypton gases);
- the introduction of coating film over the glass panes with a consequent emissivity reduction (low-emission glazing);
- the addition of interspaces splitting with multiglazing systems;
- the adoption of spacers with low thermal conductivity material components.

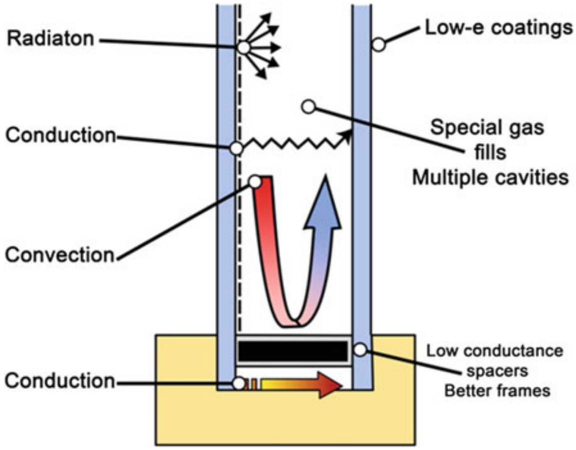


Fig. 2 Thermal transmittance conditions and improvement actions

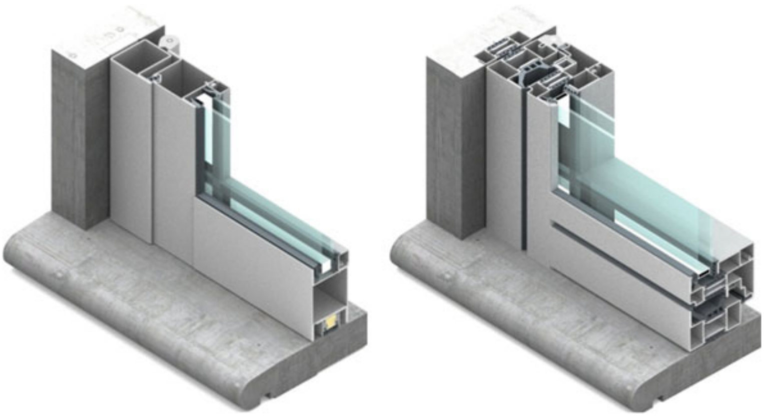


Fig. 3 Examples of typical aluminum frames without (*left*) and with (*right*) thermal break (*strips of polyamide*) (*Company METRA*)

The ideal limit occurs with the adoption of vacuum cavities between glass panes: the heat exchange is reduced to just radiation and the cavity reaches the maximum value of thermal resistance equal to approximately 0.276 m^2 K/W, with a temperature difference between glass panes of about 10 °C [7].

The thermal transmittance of the glazing U_g depends on the number, the thickness, and the interspace of glazing. U_g values are also depending on emissivity and nature of the gas in the cavity, and they can reach about 0.3–0.5 W/(m^2 K), congruently with the "zero-energy house" achievements.

The frame, along with the glass panes, constitutes the other essential components of the window; it can be made out of wood, aluminum, or metal with thermal break (Fig. 3), PVC, or mixed materials.

Historically, for doors and windows, the most common material is wood, with frame thicknesses between 50 and 60 mm, and average transmittance U_f of about 1.9–2.3 W/(m^2 K) (generally wood frames perform higher transmittance values than metal frames with thermal break).

Nowadays, to improve the performance and the durability of wooden frames, mixed solutions have been developed with aluminum on the outer side and wood on the inner side, with thermal insulation components and U_f values between 1.0 and 0.6 W/(m^2 K) (about six times lower than the values of metal frames with thermal break) [9].

3 The Radiative and Acoustic Performance

Common glass panes are transparent to solar radiation in the range of wavelengths from ultraviolet to the near infrared (from 0.3 to 2.5 μm), with a maximum peak in the visible range (about 42 % of the solar energy is emitted in the range of 0.38–0.74 μm wavelengths).

In order to control the transmission of solar radiation, a protective coating can be applied over the glass surfaces, improving the light transmittance τ_v (%) and the solar factor g (%).

Both parameters represent the average values of the energy ratio transmitted through the glass and the normally incident energy over the surface in the spectrum of standard radiation [26]. In Anglo-Saxon countries, the shading coefficient SC (%) is widely used as a valid alternative to the solar factor g. It is the ratio of the radiant energy that penetrates through the glass to the energy transmitted through a common clear glass of 3 mm thickness.

The control of radiation, primarily, is performed by increasing the capacity of reflection in the visible range, but this action is likely going to alter color perception, expressed by the general color-rendering index Ra.

The index Ra can reach the maximum value of 100 for glasses whose spectral transmission factor τ_λ is constant in the visible spectral range. For common glazing, $Ra \cong 98$ and $g \cong 0.89$.

In the field of environmental control practices pertaining to lighting design, $Ra > 90$ is featuring a very good yield, while values of $Ra \geq 80$ indicate a yield of acceptable color.

The chromaticity of glass panes, in relation to comfort, shows a comfort acceptability falling below 85 % of occupants when τ_v is reaching 38 % with cloud cover and 25 % with clear sky.

To ensure an effective protection against solar radiation, a glass must have a g value between 15 and 20 %; however, this implies a high reduction in τ_v, with consequent worsening of natural lighting, and sometimes, it can result in a Ra shortcoming [2].

The solar radiation effects could be reduced using special coated glasses, such as:

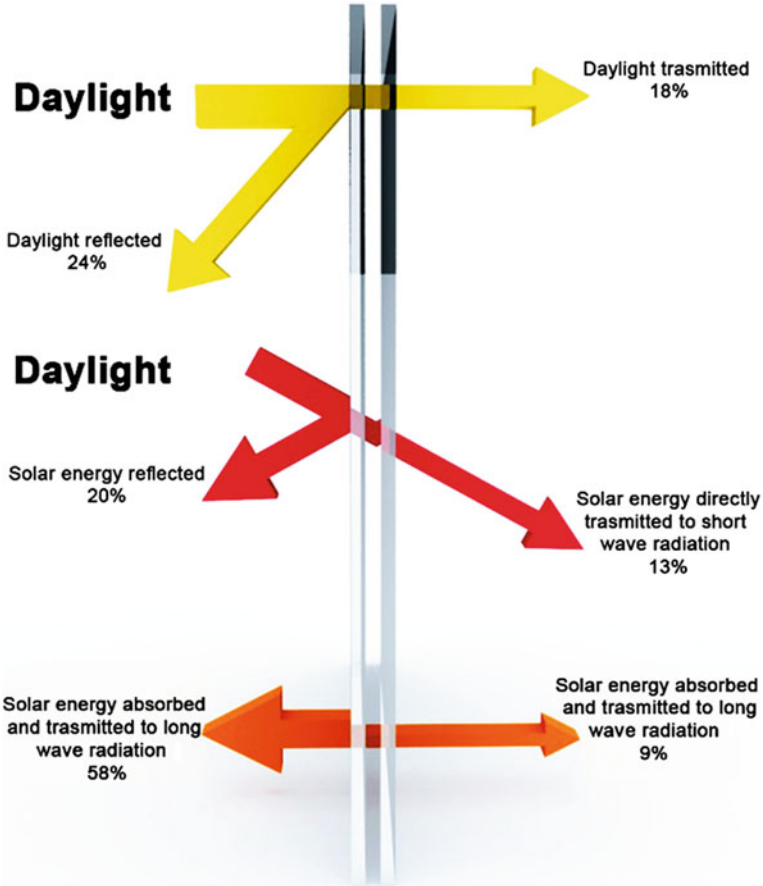


Fig. 4 Example of solar reflective glass window 6–12–6 mm, with $U_g = 2.7$ W/(m^2 K), light transmittance $\tau_v = 18$ %, solar factor $g = 22$ %, and $SC = 25$ % [17]

1. sunscreen-reflective glass (Figs. 4 and 5);
2. glass for thermal insulation—low emission;
3. low—emission glass and reflective glass(Fig. 6).

Along with coatings, the proper selection of tinted glass plays a key role in architectural design. The internal chromatic perception is the response to the light transmitted through the ranging variety of stained panes: the most common are gray, bronze, blue, and green (Fig. 5); those colors do not excessively alter occupants' perception ($Ra \geq 90$).

Moreover, a glass pane that creates a brighter light effect in rooms is more suitable (such the kind in bronze color does); usually, in hot climatic regions, cold colors are preferred and vice versa in the cold ones [3].

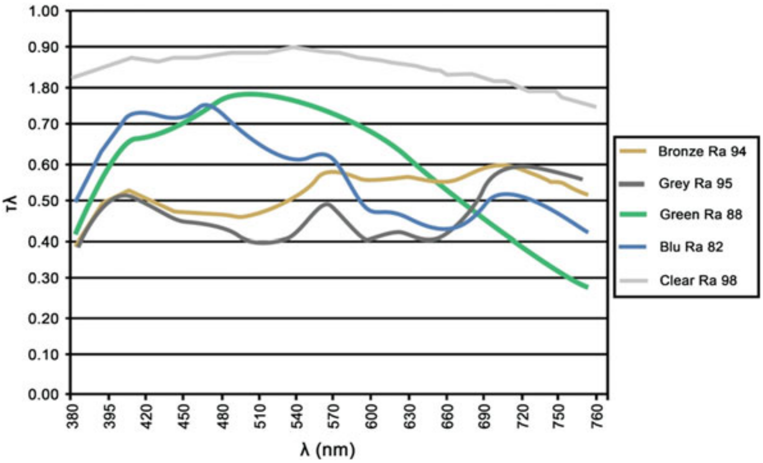


Fig. 5 Tinted glasses—spectral trend τ_λ and color-rendering index *Ra*

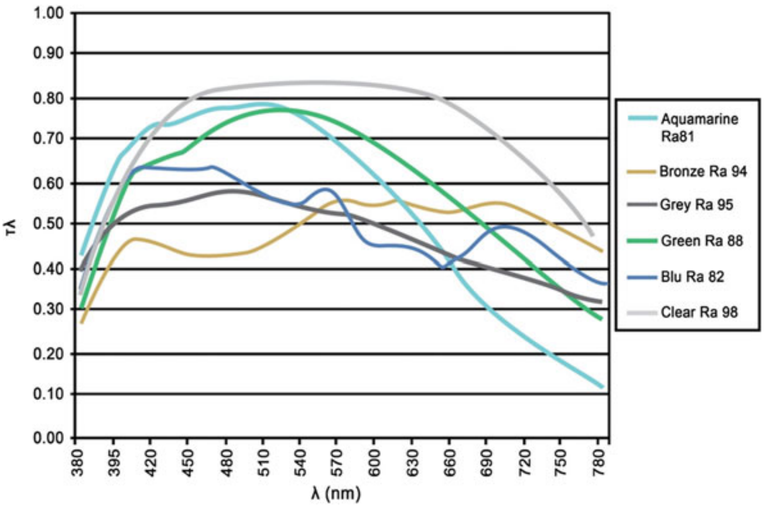


Fig. 6 Selective coated glasses—spectral trend τ_λ and color-rendering index *Ra*

In the making of choices for glass types, therefore, being aware of transitional effects from winter to summer, façade exposures, shading effects from the surrounding, etc., would be useful. Emerging technologies aim to develop glass panes with dynamic optical properties, such as the smart windows, consisting of electrochromic materials (ECWS), liquid crystal devices, or suspended particles [10]. They are capable of varying the radiative performance in function of the outside weather and the inside conditions, cutting down energy costs by 10–45 % on lighting and 5–15 % for air-conditioning in summer, up to a maximum of 20 %, compared to more conventional control systems for solar radiation.

The electrochromic glass may have a τ_v factor from 0.03 to 0.75, with thermal transmittance of $1.6 < U_g < 0.5$ W/(m^2 K) [10].

Natural light changes during the day and with the changing seasons; thus, the levels of internal lighting and external lighting are instantaneous values that are constantly changing, especially in the presence of variable sky. Consequently, it is not possible to prescribe absolute limit values of natural lighting. In addition, in clear sky conditions, the assessments should be conducted under detailed computational method procedures.

For simplicity, many regulatory and legislative codes refer to the relation between the internal lighting and external lighting at the same time; the performance indicator, the "daylight factor" (DF), is used to evaluate and express the punctual nodes of luminance levels of zones under an overcast sky, and it is defined as the ratio of internal (E_{int}) illuminance to external (E_{ext}) illuminance:

$$\text{DF} = \frac{E_{\text{int}}}{E_{\text{ext}}}$$

Since the percentage of DF varies in every point of a given environment, usually it refers to its average value. The greater the homogeneous distribution of light, the greater the internal level of comfort.

According to EN ISO 12464-1 [28], it is desirable that the ratio of minimum luminance to average luminance is ≥ 0.7 in the area of the visual task and ≥ 0.5 in the immediate surrounding area to that of the task.

The light distribution (gradient lighting) also presents spatial variations: the level of natural light decreases rapidly with increasing distance from the window (Fig. 7); the interior surfaces, including the furniture, can produce strong contrasts or reduce differences in brightness. A side sourced light presents a very different gradient of illumination from a zenithal light source, characterized by a relatively uniform distribution. An external obstacle can hinder the internal lighting.

One of the parameters used for the analysis of illuminance levels for inside spaces is the useful daylight illuminance (UDI) [13, 14]; the UDI has been defined in order to support the analysis of illumination levels by natural light, based on hourly meteorological climate data for the period of 1 year, to determine how many hours the level of natural lighting is within the range 100–2,000 lx deemed satisfactory by the users for an adequate VC in natural light conditions.

Below 100 lx, illumination values of natural light are considered insufficient to satisfy basic visual tasks. They represent a negligible contribution toward energy efficiency. Natural light levels in the range 100–500 lx are effective for many visual tasks and offer a good contribution in terms of energy savings. The illuminance values of natural light in the range 500–2,000 lx are considered satisfactory for all the visual tasks, while illuminance values >2,000 lx, in most applications, cause visual discomfort and rising of temperature.

In the evaluation of solar shading solutions, the UDI is used to evaluate the lighting properties of shielding, with "clear sky" conditions corresponding to the

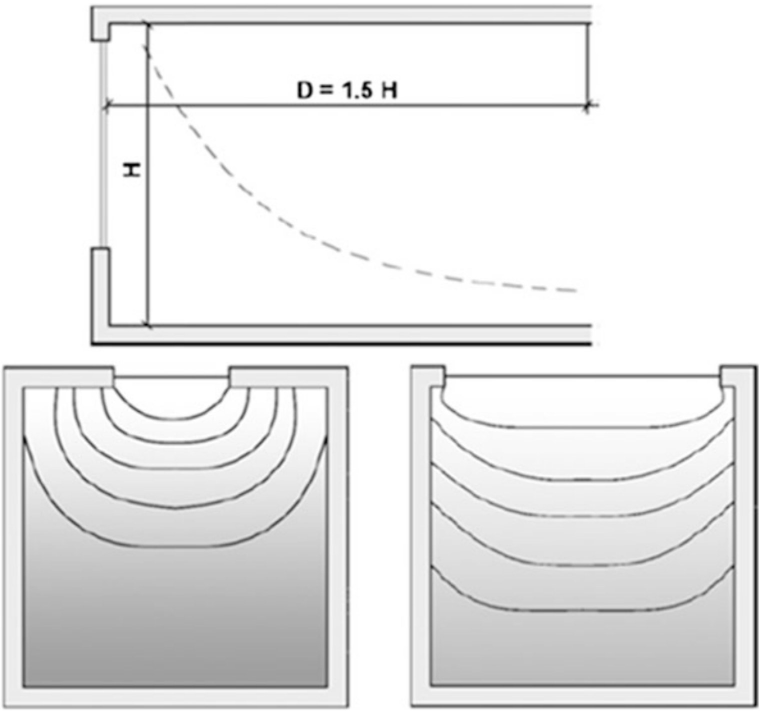


Fig. 7 Gradient lighting depends on the height (H) and the width of the window

model developed by CIE, which provides a luminance distribution as a function of the position of the sun at given latitude [18, 19].

Another fundamental aspect is given by acoustic comfort specifications, which represent a design parameter setting in all European countries. Acoustic performances are of great importance in the design of residential, considering that, very often, they are the critical part of the partitions and closures and they have to meet standards of comfort expectancies and building codes and regulations. The noise, in fact, may have effect on people's health and consequently economic implications.

With regard to acoustic performance of windows and shading devices, they are expressed by the index of evaluation of the sound reduction R_w (dB) [5]. Another fundamental aspect to ensure the expected performance is related to the tightness of the frame [21], which must be as highest as possible; otherwise, the penalty may also be of several dB.

The acoustic performance of a window is conditioned in order of importance by [4, 24]:

- the type of glazing (single glazing or laminated);
- the number and thickness of glasses (mass of the component);
- the tightness of the frame (type of seals and number of beats).

The installation procedures need proper attention, as they have to be performed, for example, without creating sound bridges at the frame–masonry junctions.

Summarizing as a reference of the above-covered contents, the following performances are listed below:

- solar factor $g \leq 0.50$;
- light transmittance $0.38 < \tau_v < 0.65$;
- color-rendering index $Ra \geq 90$;
- thermal transmittance $U_g \leq 1.3$ W/(m^2 K);
- rating of sound reduction index R_w of the window ≥40 dB.

4 Windows' Typologies

The general term of "external openings" widely refers to several technical elements such as fixed windows and operable windows (by single-hung or double-hung sash, horizontal sliding sash, awning, hopper, tilt and slide, and tilt and turn) jalousie window, clerestory, roof lantern, skylights, French doors etc.

According to the definition given by the standard [25], the window is a building component for closing an opening in a wall or pitched roof that will admit light and may provide ventilation.

The current production of windows can be classified according to:

- type of opening;
- type of frame materials;
- type of glass;
- type of spacers between the panes.

Each of the above typology components can lead to issues, mostly in terms of acoustic and thermal bridges; both of these aspects are inherent to the technology implied in the manufacturing and in the installation procedures.

4.1 Installation

The installation procedures of windows must attend to the main requirements of:

- control of thermal bridges through the window framing and the wall system;
- control of sound transmission through the window framing and the wall system.

Both of these requirements have to be fulfilled; otherwise, good energy-saving windows may have their performance diminished as a result of a poorly proceeded installation.

4.2 Thermal Bridges

An important reference supporting the first requirement is the EN ISO 14683 [29].

Looking at the various typologies of thermal bridges, the most critical conditions can be identified as those having a maximum value of linear thermal transmittance Ψ. These are constituted by:

- window positioned on the outer side with Ψ between 0.8 and 1 W/(m K);
- window positioned at the center of the wall with Ψ between 0.6 and 1 W/(m K);
- window frame positioned on the inner side of the masonry with Ψ between 0.8 and 1 W/(m K).

The best solutions with values $\Psi \leq 0.20$ W/(m K) are those with the frame resting directly on the insulating layer.

4.3 Sound Control

The situation in terms of sound control is more detailed and complex, considering the crucial importance to achieve sound capabilities of the insulation layer concerted with the choice of obscuration (blinds or shutters). Also, the inevitable uncertainties and worsening factors need to be considered, related to the construction conditions of the various components of the façade. In this regard, building guidelines that provide specific indications for proper installation (for example, the Italian standard [30]) are useful references.

Once the type of windows has been identified, the next task is to define some details on the wall opening that are critical to keep the building envelope sealed from water, air, and heat transfer and also to maintain high sound insulation performances.

In particular, the wall opening, enforced by the introduction of a wall curb sill extruded over the jamb perimeter (Fig. 8 left), may reach an acoustic performance better than the simple frame system lying flashed along the exterior wall casing (Fig. 8 right), through which sound waves can propagate more easily toward the internal environment.

A careful handling of dimensional tolerances is an unavoidable precaution to prevent serious consequences during the window installation process. It is recommended a tolerance with at least 5 mm per side between window frame and wall opening, variable in function of frame materials, solar radiation absorption capabilities, frame color and size (PVC in dark color is quite sensitive, for instance, to thermal expansion).

Bad junctions between masonry and window, small holes or poor realizations of the attack, can affect the overall result, with reduction in more than 10 dB of sound insulation.

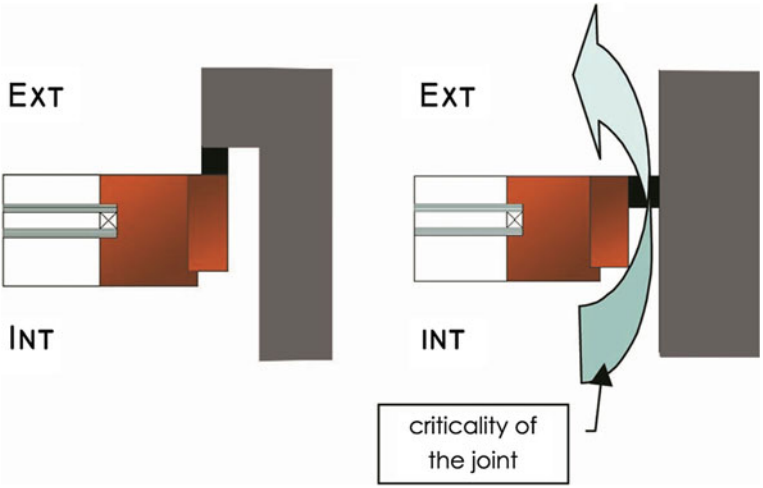


Fig. 8 Example of a wall curb sill extruded over the jamb of the window frame (*left*) and window frame flashed along the exterior wall casing

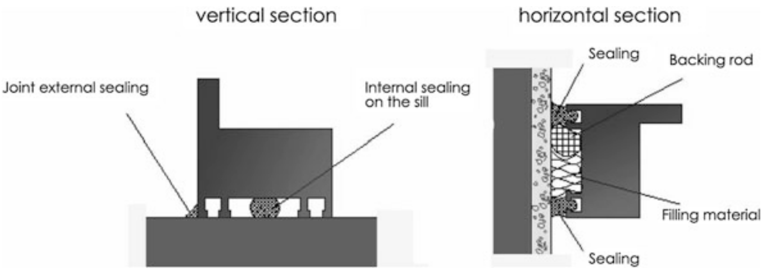


Fig. 9 Example of realization of a coupling in light

In case of window shutters lying on the middle line of the wall section (Figs. 9, 10), a bead of sealant should be applied on the three shoulders of the window opening and the sill, making sure to connect them. Once fixed the window frame into the wall compartments, it is necessary to perform the operation of filling the joint with expanding material and to seal properly the inner part of the joint with sealant; then, the interstice between the masonry and the window frame must be sealed by proper material.

Another important element is the interface frame since that, if poorly executed, can compromise the overall operation of the window.

Poorly executed installation of the glass pane interfacings can also produce issues related to sensible deformations over the frame profiles (for instance, the excessive weight of the glass plates can reduce the air tightness of the frame and therefore affects the sound insulation performance).

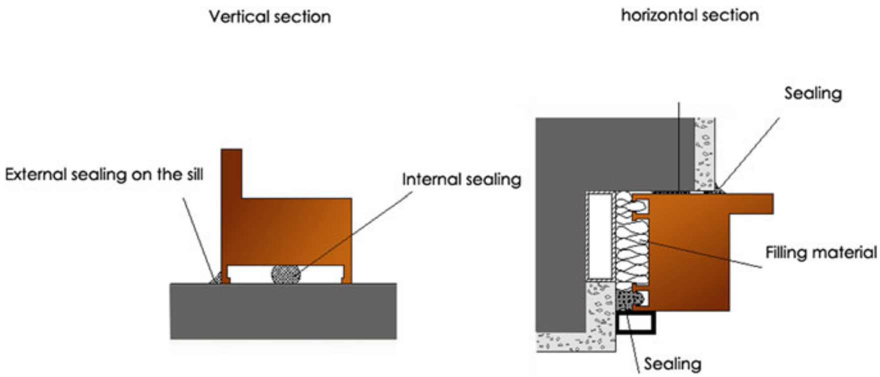


Fig. 10 Example of construction of a joint in abutment

In this respect, the proper sizing and positioning of the blocks are important. These procedures contribute to relieve the weight of the glass plates over the frame and to keep them in the right position, avoiding movements of the sheets of glass chamber.

4.4 Window Rolling Shutter Casing

Particular attention has to be paid to the installation of window rolling shutter casing, since it may cause several weaknesses in terms of sound insulation.

The installation must ensure that both the casing box and the maintenance door are secured by durable gaskets with a suitable grade of elasticity.

In the case of prefabricated rolling shutter casing, the material space between the wall and the prefabricated block on the shoulders, laterally and above the casing itself, must be filled carefully with mortar or expanding materials.

Depending on the type of opening, windows may have major or minor shortcomings in terms of thermal and acoustic performances (it should be also considered the opportunity given by hopper window and tilt and turn window).

Among the various types of windows, the ones that ensure the best possibility of sealing, and consequently the best thermal and acoustic performances, are those with one leaf, namely those that, for the same frame and surface, have the lowest perimeter of the stop.

The two doors' frames can have opening inward or outward and an opening in rotation around the two vertical side axes, therefore with a very critical stop perimeter than the one door window.

An alternative can be represented by the revolving door window, with an opening in rotation on the vertical axis or on the horizontal axis (horizontal hovering). When fitted with a locking mechanism, the ventilation is permitted without full opening.

Bottom hinged windows are essentially conceived for services or workplaces to allow ventilation; in today's residential buildings, they are often replaced by sash windows with a turn and tilt opening system.

For windows with important surface area opening, sliding horizontal doors are often adopted. These types of frames, which are difficult to seal, have been recently improved by the introduction of the sliding coplanar door windows that align on a track the two sides of the window. The coplanar sliding doors have a double system of opening: sliding door and hopper.

The so-called foldable windows, composed of multiple door components that can be folded, are much more critical, especially under the acoustic profile.

4.5 Frames

The frames can be classified according to the system of beaten into three categories:

- Windows with single beaten;
- Windows with double or triple stop beatens;
- Window frame with open joints.

The frames with single stop profile have a simple single seal, which has to guarantee air and water tightness; therefore, it is generally not reliable, especially in the presence of high external pressure, when the wing tends to inflect the frame itself causing the detachment of the gasket. At this purpose, the sealing of windows with double or triple stops should be preferred.

A further evolution consists of the introduction of an open joint between fixed frame and opening section, providing a capillary break, which prevents water seeping in and lodging in the joint. The central gasket allows to drain the water eventually penetrated inside, through the drain holes, using an equilibrium phenomenon of internal pressure to the external one.

The mechanical performances required for the casing are:

1. air tightness;
2. water tightness;
3. resistance to wind;
4. mechanical resistance.

The choice of the energy classes for exterior windows has to be performed considering the characteristics of the building and the climatic conditions of the specific environment. In addition, the performances must be appropriate to the size, type of windows, and levels of thermal and acoustic insulation required within the living spaces.

4.6 Permeability, Water Tightness, and Wind Resistance

Windows can be cataloged into four classes with regard to air permeability [20], into about 18 classes for their water tightness [22] and in seven classes with regard to wind resistance [23].

5 Solar Shading Typologies

The evolution of the environmental control techniques combined with the support of detailed computational software inquire to the designer a careful choice of shading devices in the building design, in order to ensure the consumption control during summer times and to provide comfort for the occupants [15].

In general, a screening system can be applied to the right-angle frame of the entire building or a portion of it, adding also a value to the renewal of the façade design, so that their application allows a new perception into existing buildings.

A well-conceived shading device must be able to maximize heat gains in winter conditions and to control the radiant heat in summer conditions, as well as to improve visual and acoustic comfort of the interior.

Accordingly, the effectiveness of sun protection of glass surfaces depends on different factors:

- characteristics of the screen materials and finishing (reflectance);
- solar shading solution (fixed or mobile). A fixed solar shading (canopies, balconies, frames, etc.) does not allow variation in energy responses; on the contrary, mobile shading devices permit, manually or by automated systems, to adapt to the sun path daily and yearly, due to a punctual control of the shading elements to ensure natural light maximum efficiency;
- screen positioning with respect to the frame (external, internal, intermediate). The outer shields are most effective, intercepting the incident solar radiation before the glass panes and preventing therefore the greenhouse effect. Furthermore, the placement of the shielding outside also allows to interact with the outer sound waves (for instance traffic). Thus, if properly designed, external shielding can help to significantly reduce the sound pressure incident on the façade;
- screen disposition, according to the façade exposition (parallel, orthogonal, horizontal, vertical, etc.), geographical location, and thermal loads. Often, the shield with vertical fixed elements is conceived for the areas facing east and west on which solar radiation affects the morning and late afternoon, with a lower height on the horizon profile. The system that places the fixed elements perpendicular to each other, called "grating", is one of the most suitable for shielding glass surfaces located at the east and west side in hot climates, but these elements are hardly applied in residential buildings and are most used in public and industrial ones, due to the strong architectural language they impose.

All the sun protection systems installed in front, or on the outside of the frame, without making the same body, are external sunscreens, by definition.

Solar shading device can be defined as a "screen attached to the outside of the wall that consists of several horizontal or vertical elements with the function of sun radiant energy mitigation."

Outdoor sunscreen solutions bring higher added value both in terms of architecture and in terms of economic performance; external shieldings, much more effective than internal ones, are usually more expensive and subject to maintenance, since they are permanently exposed to atmospheric agents. The type of material of screen components plays a fundamental role.

The blinds elements are mostly made out of extruded aluminum or galvanized steel and painted. There are also brise-soleil made out of other materials such as wood, brick, PVC, and copper. Whatever the material employed is, the device must ensure adequate operability and aesthetic value over time; in this regard, metals, properly treated and painted, have effectively replaced wood, more prone to deterioration.

The selection of external shielding components should take into account the outdoor weather conditions and the device wind resistance, since, under high wind loads, the system can suffer major damages. With regard to blade sections, there are several possible configurations: ellipsoidal, curved, gull wing, triangular, diamond-shaped, and rectangular (for wooden ones).

The several solutions for external shielding can be classified into four main product families:

- fixed shading;
- mobile shading;
- roller blinds;
- curtains.

5.1 Fixed Shading

These systems are commonly constituted by a shield of linear panels or slats, mounted in parallel on a fixed or adjustable frame, to form a pattern to intercept the solar radiation. Figure 11 shows some examples of fixed shading.

Sunscreens are installed in front of the window with preoriented blinds or blades, creating a kind of outer curtain. Generally, the blades are always geared according to the sun incidence of the hottest period of the year.

These systems may become a very important formal element in the project, if they are interpreted as a real envelope.

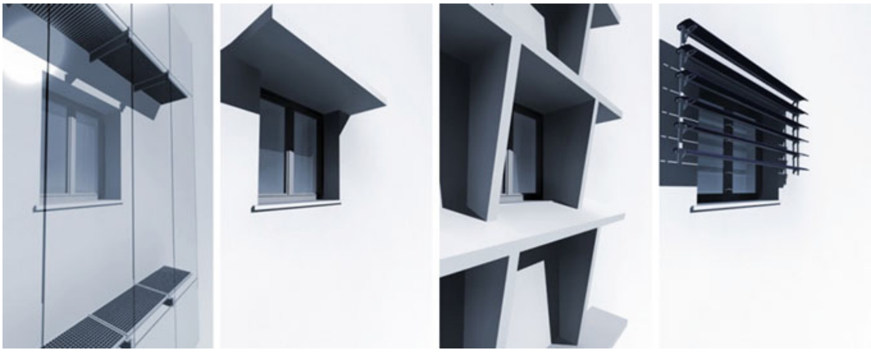


Fig. 11 Examples of fixed shading (from the *left* horizontal sunscreen, fixed overhang, grating and sunscreen, fixed blades)

5.2 Mobile Shading

This solution, featured to shield the building from solar radiation, by modifying the blinds or blades angle, allows to optimize the amount of natural light. Figure 12 shows some examples of mobile shading.

The devices that rely on blinds are installed horizontally to the façade, while those with blades can have a vertical application too. Vertical blades are smaller in size and can rotate by about 180°; it is a product used primarily for industrial application. The rotation of the blades allows to shield the radiation and to reflect it into the enclosure by adjusting the flow. This system, usually of significant dimensions, is lacking of the capability to eliminate all the shield obstruction, when not required, since the blades attached to their pivot are not packable.

Shadings with horizontal blades have larger dimensions to accomplish aesthetic purposes and to resist against the wind. These devices come with various section profiles (the most common is ellipsoidal), with large intersection, and can be automated by light sensors which allow a continuous variation according to the daily sun path.

The so-called Venetian blinds are very similar to the Venetian curtains: the main difference is in the size of the blinds. They consist of a cloth made out of painted aluminum planks or slats of various shapes and sizes hanging from a ladder tapes. The slats are driven through a mechanisms housed in the upper casing; along the sides, lateral guides or aluminum wires are provided. The key feature is the ability to top packaging into a very small space that favors their use even in residential building renovations, where there is not much available space and the option for façade inclusions does not meet the aesthetic expectations or the regulatory requirements.

Persian blinds consisting in sliding or folding doors, also with operable slats, are widely used in residential constructions and can be produced in different materials such as wood, aluminum, and PVC. The choice of suitable materials, in addition to aesthetic reasons, is also linked to maintenance needs.

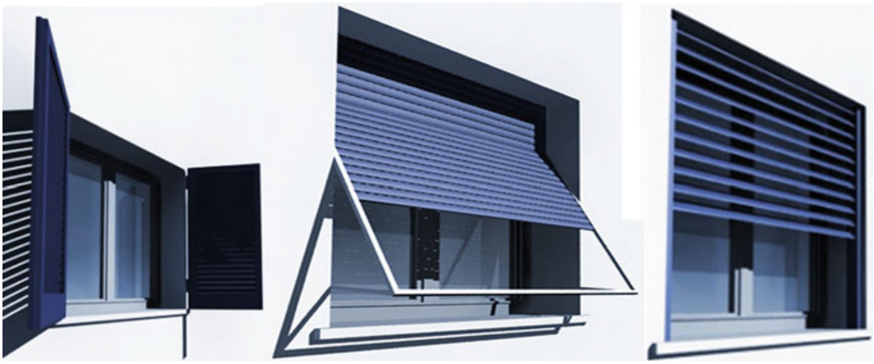


Fig. 12 Examples of mobile shading (from the *left* persian shutters, roller blinds, and Venetian blinds)

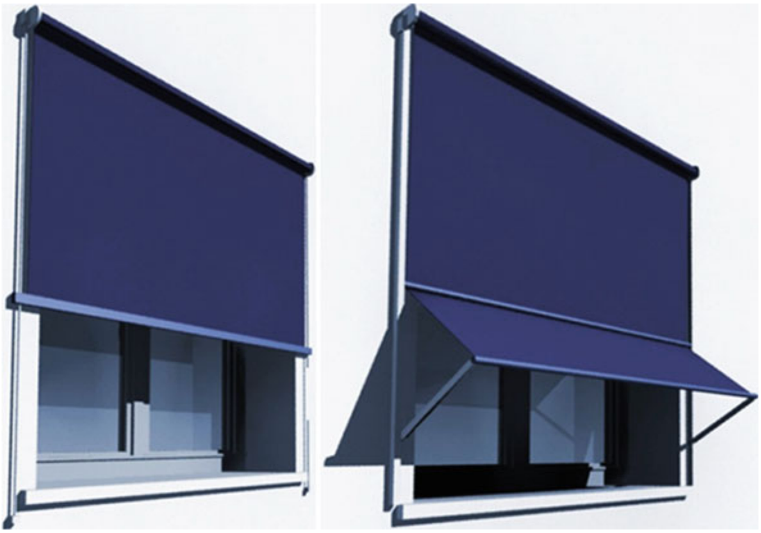


Fig. 13 Examples of roller blinds (*left* roller curtain; *right* sliding arm awning)

5.3 Roller Blinds

These systems are widely used, due to the simplicity of the mechanism (spring-roller-operated, gearbox, or engine that wraps around the curtains) and also due to volume-saving characteristics, (Fig. 13).

From a solar control point of view, the degree of response depends exclusively on type, color, and weight of the fabric used.

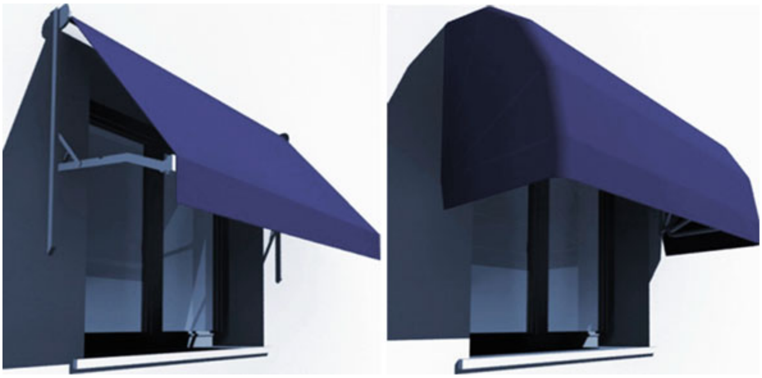


Fig. 14 Examples of curtains (*left* drop-arm awning, *right* tent canopy)

5.4 Curtains

This family of screens includes various typologies and models, which ensure the protection of façade from solar radiation with limited costs and flexibility. Being very exposed to the elements, raw materials of high quality and sophisticated finishing are used to maintain unchanged the aesthetic and functional characteristics of the system itself (Fig. 14).

The drop awnings are often visible on balconies or directly build into the façade system, installed vertically, with variable size, overhang in order to close the openings and shading the area that lying below them.

Curtains may also have a foldable and retractable structure and can be installed in horizontal or tilted plane up to 90°; in addition, this type of installation facilitates proper ventilation of the spaces below. Nowadays, the performance of the tent fabrics is crucial on market competition. These components must have the ability to mitigate solar radiation, durability, and waterproofing capability. The most common fabrics are made out of glass fiber or polyester yarn both coated with PVC for weathering protection purposes.

A variation is represented by fabrics screened by an undercoating of PVC film, in order to permanently close the wefts of the tissue. This type of textile provides a heavy and stiff coat and therefore is used only in highly demanding applications.

5.5 Internal Solar Shadings

The inner shields are less effective from an energy point of view than the outer ones; thus, they are usually added to them to further control solar radiation, daylighting, and glare and to ensure privacy for occupants. Moreover, their

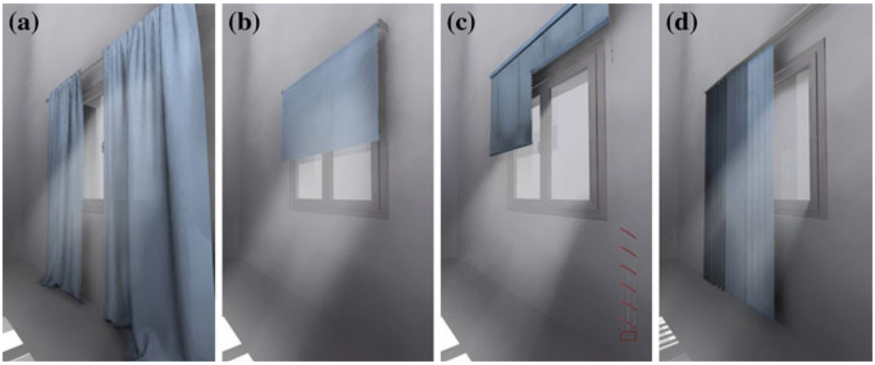


Fig. 15 Examples of internal blinds (from the *left* classic drapes, roller drapes, Venetian blinds, and vertical curtain)

capability to mitigate the sound pressure coming from the outside is negligible (Fig. 15). The principal products for internal application include:

1. translation systems (panel curtains and skylights);
2. chutes (roller blinds and pleated blinds);
3. systems to strip (horizontal Venetian blinds and vertical louvers).

5.6 *Intermediate Solar Shading*

One possible solution of combining the glazing with shielding systems derives from the existing Venetian blind systems, with smaller scale blinds to be placed in the cavity of the double glazing. This hybrid system provides a satisfactory level of solar radiation control and represents an efficient alternative to those previously described.

The system ensures an adjustable filter to the entrance of sunlight: the amount of light can be adjusted from 80 % total obscuration and instantly adjusting the brightness depending on the demand (Fig. 16).

The blinds are mounted within two panes of glass, and their scrolling takes place in a sealed chamber. This feature ensures total protection against dust and weather. The solution presents durability and maintenance issues.

There are many versions of this system, each with its own mechanical solution, aimed to solve the handling without compromising the seal of the glazing panel (mostly there is a magnetic slide system and motorized system).

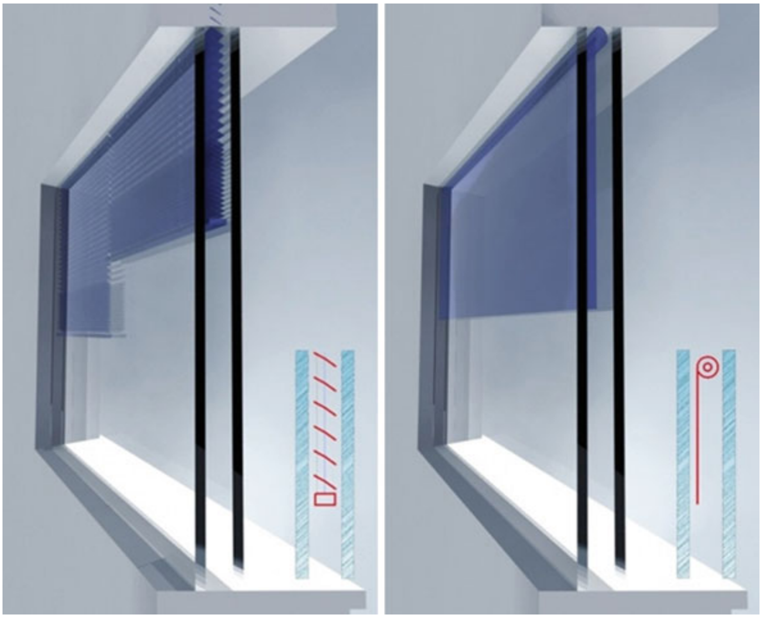


Fig. 16 Examples of integrated screens (from the *left* Venetian blind and roller blind)

6 Integrated Solutions Applied to a Case Study on Existing Buildings

The evaluation of different strategies for upgrading the energy efficiency and performance over various types of shielding needs to be explained by a case study. A typical room was taken into account, with features and dimensions representative of typical post-World War II Italian residential architecture (Figs. 17, 18).

Different strategies concerning windows and solar shadings have been applied; for each one, thermal, daylighting, and acoustic performances were assessed with appropriate calculation codes.

6.1 Case Study Description: Significant Parameters

For the purposes of the analysis, detailed computational methods working in dynamic regime and featuring a graphical interface are considered. These software applications are the following: EnergyPlus (through the Design Builder interface) for energy simulations [12], RELUX [16] to simulate natural lighting, and DISIA for the acoustic simulations [11].

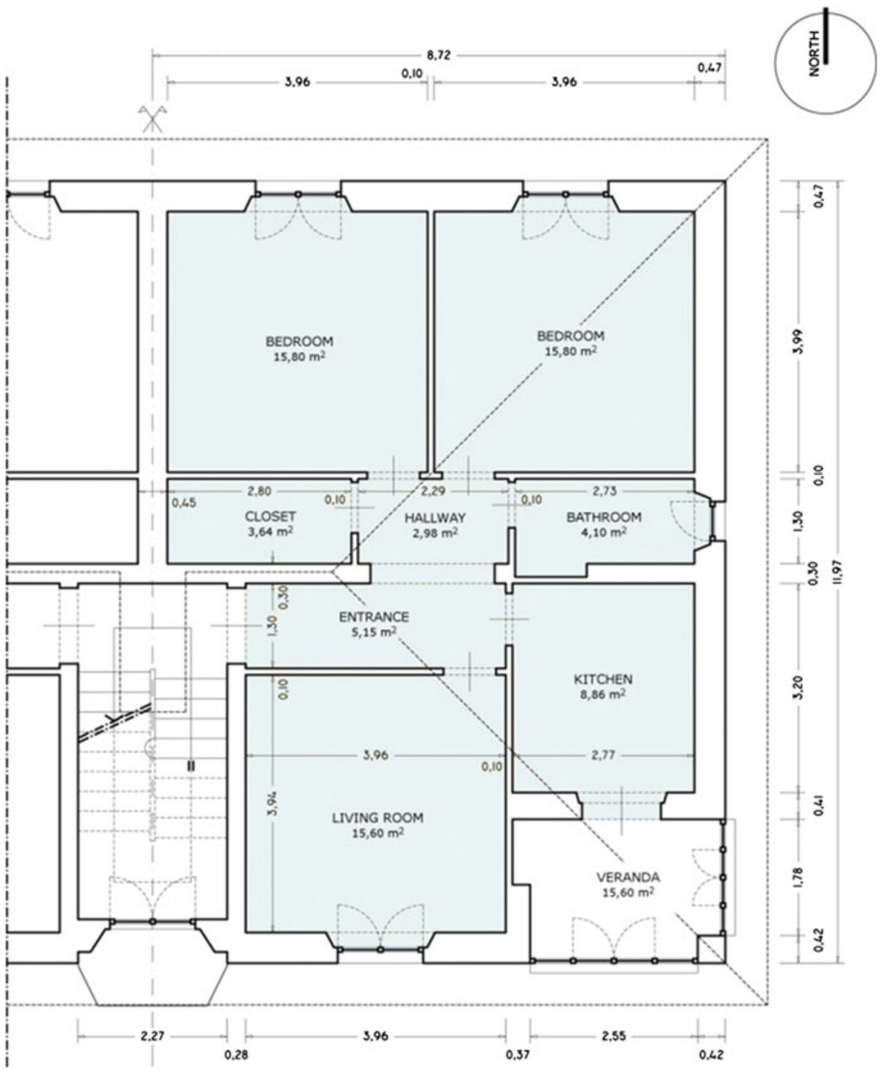


Fig. 17 Plan of typical floor analyzed

Once defined the calculation codes more suitable for the objectives of the project, the knowledge of the environment peculiarities of the building site becomes fundamental.

In the following, the reference to four locations is considered: Berlin, Milan, Florence, and Athens (Table 1).

As for the energy simulations, for each weather zone, the dry bulb temperature of the outside air (θ_{db}) and the solar radiation (I_{sol} expressed in W/m^2) over the various orientations are required to evaluate thermal loads during winter and summer times.

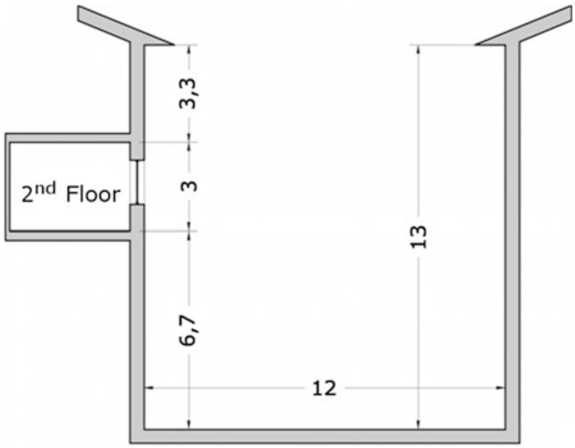


Fig. 18 Hypothesis of the urban context (section)

Table 1 Locations considered in the analyses

Location	Heating period	Cooling period
Berlin	1/10–30/4	1/6–31/8
Milan	15/10–15/4	15/5–30/9
Florence	1/11–15/4	1/5–15/10
Athens	1/12–15/3	1/5–15/10

The hourly values of dry bulb outdoor air temperature and solar radiation to perform the energy simulations are gathered from the Institute "Gianni De Giorgio" (IGDG) [31] archive, for Milan and Florence, and from the International Weather for Energy Calculations archive, for Berlin and Athens.

The case study shows dimensions of 4 m by 4 m in plant and 3 m in height of the ceilings. In Fig. 19, the geometrical features and the position of the window are shown and in Fig. 20 the case with the French door is presented.

It is assumed that the room is located on the second floor (height from the road level equal to 6.7 m) of a 4-storey building, 13 m high. The cell type used for the calculations is reported in Figs. 19 and 20.

For the specific purposes of the lighting evaluations, the light reflection coefficient of inner surfaces has been assumed equal to 0.6 for the walls and ceiling (plaster and furniture in clear color) and 0.4 for the floor.

The light reflection average coefficient of the external surfaces and of the front building façade was assumed to be equal to 0.6, and then, three walls of the cell and the two horizontal partitions are considered adiabatic. The window is located in the fourth wall, which presents thermal losses depending on the orientation. Therefore, different case studies are evaluated (North, South, West and East).

The basic configuration of the cell presents a mixed masonry external wall, plastered on both sides, of 0.47 m total thickness. The window is single-glazed with 3-mm-thick panes, and the wooden frame is 50 mm thick, corresponding to

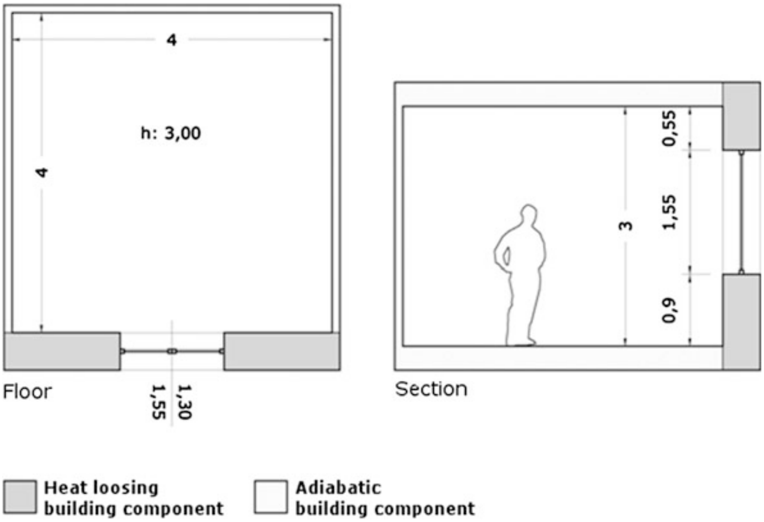


Fig. 19 Plan and section of the case study

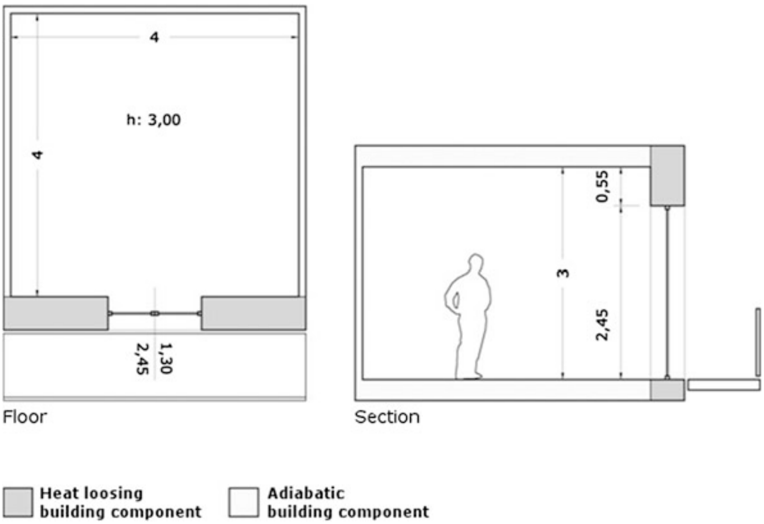


Fig. 20 Plan and section of the case study with French doors onto a balcony

20 % of the surface of the window frame. Tables 2 and 3 show the main thermal and acoustic performances of the external wall and of the window.

Appropriate performance indicators (defined by regulations or conventionally applied) should be identified, in order to evaluate different strategies for the achievement of energy efficiency and of comfort requirements. The same indicators can be applied to compare energy consumption, lighting, and acoustic improvement solutions suggested through the analysis procedures.

In the current case study, the following performance indicators were identified, to evaluate the energy performance of different refurbishment strategies:

Qs_w Winter solar gains (kWh);
Qs_s Summer solar gains (kWh);
θ_o Operative temperature (°C);
F_w Reduction factor of winter solar gains (%);
F_s Reduction factor of summer solar gains (%).

Qs_w and Qs_s represent the solar thermal gains transmitted through the glass panes of area A_g, evaluated during heating (W) and cooling (S) period, in relation to the incident solar radiation I_{sol}, from the glass area A_g.

Seasonal reduction factors (F_w and F_s) are calculated as the complement to the unity of the ratio of the solar gains transmitted through the glass on an hourly basis, respectively, in winter Qs_w or in summer Qs_s to those of the reference case.

These indicators can be used to compare the solar gain reduction effectiveness over a building with or without the adoption of solar shading devices.

To evaluate the performances of different lighting strategies, the following parameters were applied:

DF Average daylight factor (with standard overcast sky) (%);
UDI Useful daylight illuminance (–);
E_{min}/E_m Daylight uniformity (with standard clear sky) (–).

The average DF indicates the percentage of natural light in the indoor environment in overcast conditions.

The UDI is referred to annual time series of absolute values for illuminance predicted under realistic skies generated from standard meteorological datasets. It expresses the annual occurrence of illuminances on the work plane, where all the illuminances are within the range 100–2,000 lux. The degree to which UDI is not achieved because illuminances exceed the upper limit is indicative of the potential for occupants' discomfort [13, 14].

The uniformity of natural light (E_{min}/E_m) provides information on the inner distribution of lighting, with clear sky. It represents an important factor, because a poor distribution of natural light leads to increase the need for artificial light and thus energy consumption for lighting.

The "clear sky" model corresponds to that described by the International Commission on Lighting (Commission Internationale de l'Eclairage—CIE) [18, 19], which provides a luminance distribution as a function of the sun position at a given latitude.

The acoustic response of the vertical envelope composition has been weighted by determining the following parameters:

$D_{2m,nTw}$ Standardized façade sound level difference (dB);
ΔL_{fs} Façade shape level difference (dB).

Table 2 Performances of the opaque external wall

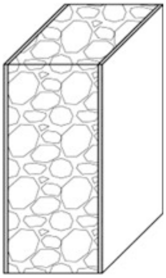
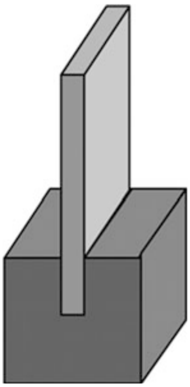
	*Thermal performance*	
	Transmittance U	1.45 W/(m^2 K)
	Periodic thermal transmittance Y_{IE}	0.152 W/(m^2 K)
	Phase shift φ	14.19 h
	Acoustic performance	
Lime plaster and cement $s = 2$ cm	Sound reduction index R_w	56 dB
Masonry clay bricks and rubble $s = 43$ cm	Noise absorption coefficient of the external surface (63–4,000 Hz)	0.05–0.04–0.02 0.04–0.05–0.05

Table 3 Performances of the window

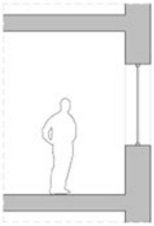
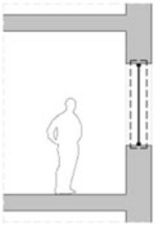
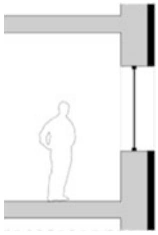
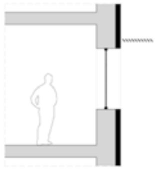
	*Thermal performance*	
	Glass transmittance U_g	5.8 W/(m^2 K)
	Frame transmittance U_f	2.4 W/(m^2 K)
	Window transmittance U_W	5.33 W/(m^2 K)
	Glass solar factor g	0.87
	Acoustic performance	
	Sound reduction index R_w	28 dB (EN 12354-3)
Wood Frame $s = 5$ cm	Air tightness class	1 (EN 12207)
Clear glass single pane $s = 3$ mm	*Lighting performance*	
	Glass light transmission factor τ_v	0.80

The sound insulation of the façade has been determined from its shape and surface, the performance and surface of single components, and the type and quality of the sealing of the joints, as specified in EN ISO 12354-3:2000. The façade shape level difference has been simulated using the technique of ray tracing, taking into account the following variables: geometry of the system, absorption of façade components, and sound spectrum of the source.

Defining a consistent evaluation methodology in terms of energy, lighting, and sound efficiency of design strategies is crucial.

The analysis methodology hypothesized in this study refers to the most frequent sequence of the building energy refurbishment that can be found in several

Table 4 Summary of the simulations phases performed in this study

Phase A	Phase B	Phase C	Phase D
			
Existing building	Replacement of existing windows	Replacement of existing windows and improvement in the thermal transmittance of opaque envelope	Replacement of existing windows, improvement in the thermal transmittance of opaque envelope, and introduction of solar control systems

practical cases (Table 4): in existing buildings, the replacement of windows (49 %) is followed by the improvement in the energy performance of opaque vertical envelope (30 %).

Starting from the performance evaluation of an existing building (phase A), the study provides for the assessment of the following interventions (phases B–D), according to a logic consequential implementation performance:

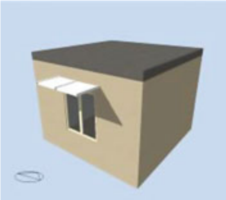
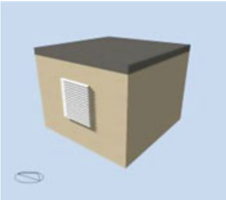
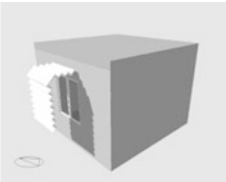
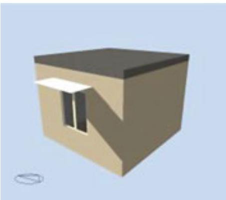
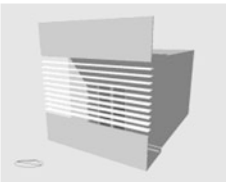
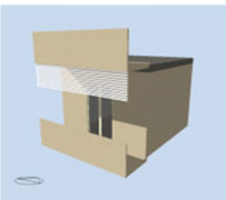
- replacement of existing window with a high-energy performance one (phase B);
- adaptation of the thermal transmittance of opaque envelope to national legislation limits (phase C);
- introduction of solar control systems (phase D).

In the phase D, the configuration corresponding to the phase C is associated with different screening systems. As an alternative to screening systems, the performance of two different solar control glasses, which, respectively, present $g = 0.46$ and $\tau_v = 0.58$ and $g = 0.21$ and $\tau_v = 0.40$, has been evaluated.

The selection criteria for shading systems (Table 5) follow the requirements for the reduction in energy consumption in summer and in winter and the achievement of the best possible comfort keeping the view of the external environment in all seasons [15]. Among the possible materials available on the market, for weight and installation advantages, a metal product (aluminum) has been chosen; its white shining color reflects incident solar radiation, both direct and diffuse, with hemispherical uniform distribution.

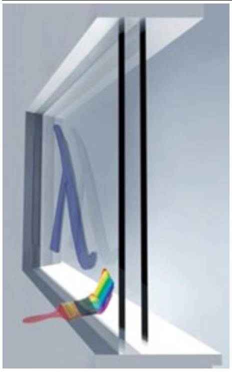
Specifically, about the coating treatment and the overall performance the reference are the EN 14351-1, EN 15193, EN 10077-1, and the EN 410 standards.

Table 5 Schedule of different types of shielding analyzed in phase D

	D1.1—Sunshade with continuous horizontal blinds (tilting: 30°, 60°, 90°) Blind dimensions: 0.08 m × 0.90 m Step between the blinds: 0.08 m Overall width: 1.90 m Overhang: 0.8 m Distance from the window: 0.2 m
	D1.2—Venetian blinds (tilting: 0°, 30°, 60°) Blind dimensions: 0.08 m × 1.3 m Step between the blinds: 0.08 m Distance from window: 0.1 m
	D1.3—Sunshade with continuous horizontal and vertical screens Blade dimensions: 0.2 m × 1.5 m Step between the blades: 0.2 m Overhang: 0.8 m Distance from the façade: 0.8 m Distance from window: 0.8 m
	D1.4—Overhang opaque fixed horizontal Overhang: 0.8 m Width: 1.9 m Distance from the window: 0.2 m
	D1.5—Vertical sunshade with blades tilted integrated with balcony (tilting: 0°, 30°, 60°) Blind dimensions: 0.2 m length × façade Step between the blades: 0.2 m Balcony depth: 1.2 m
	D1.6—Vertical sunshade with blinds tilted integrated with balcony (tilting: 0°, 30°, 60°) Blind dimensions: 0.08 m length × façade Step between the blinds: 0.08 m Shielding height: 0.8 m Balcony depth: 1.2 m

(continued)

Table 5 (continued)

	D2.1—Solar control glass $g = 0.46$ $\tau_v = 0.58$ $U_g = 1.60$ W/(m^2 K) $U_w = 1.77$ W/(m^2 K) D2.2—Solar control glass $g = 0.21$ $\tau_v = 0.4$ $U_g = 1.60$ W/(m^2 K) $U_w = 1.77$ W/(m^2 K)

6.2 Effect of Screens and Windows on the Summer Thermal Loads and Thermal Comfort

The presence of glass surfaces ensures winter favorable thermal gains; however, in summer, it may cause interior overheating by the sun.

Recently, the replacement of windows in existing buildings has become common practice, thanks to tax incentives offered in certain European countries, to the ease of implementation, and to the synergy of positive effects that the intervention may produce (for example, the improvement in the acoustic performance of the façade). This action presents a great deal of technical feasibility (TF) since it rarely involves outside interventions, for example, with scaffolding, and does not interfere seriously with the activities inside rooms.

Divided by location and window orientation, Fig. 21 shows the effects on the reduction in solar gains resulting from the replacement of a window of a typical building of the second post-war period (phase A, $U_w = 5.33$ W/(m^2 K), $g = 0.87$), with a high-energy performance window (phase B, $U_w = 1.77$ W/(m^2 K), $g = 0.58$).

The figure highlights the critical regime of the West orientation in summer and the need for a conscious choice of solar shading system to control the solar radiation loads, without penalizing winter solar gains, which represent an important contribution, especially with regard to the South orientation, in terms of energy savings.

An additional factor to be taken into account during the replacement of windows is the influence that the position of the frame with respect to the façade (at the outer edge, on the center line, and at the inner edge) can have on solar loads and consequently on the need for air-conditioning.

For instance, for the climatic conditions of Florence, as shown in Fig. 22, the position of the window with respect to the façade involves, in the transition from the inner to the outer edge, an increase in winter solar gains between 48 % (North

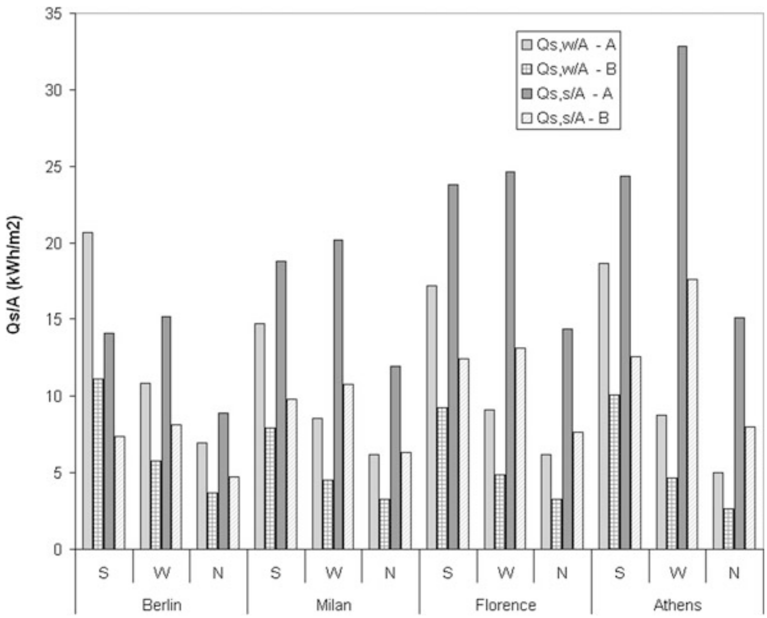


Fig. 21 Winter (Qs_w) and summer (Qs_s) solar gains per unit floor area, selected by location and window orientation relatively to the phases A and B

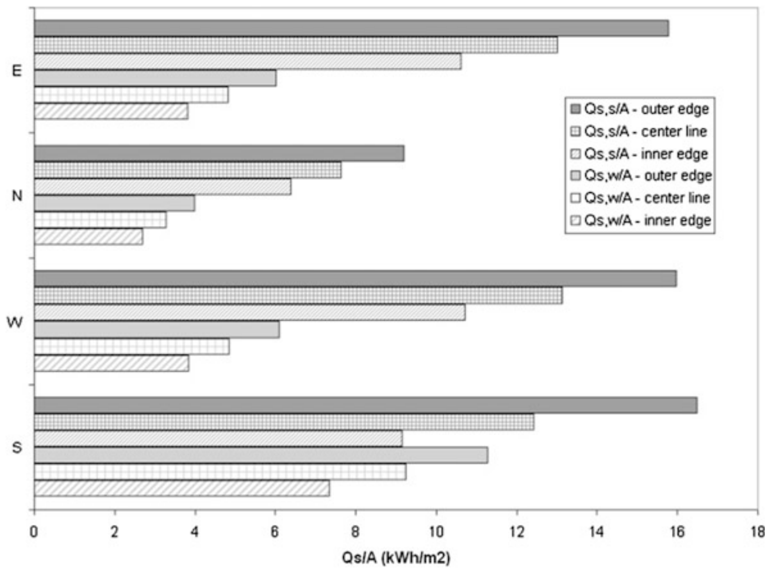


Fig. 22 Winter (Qs_w) and summer (Qs_s) solar gains per unit of floor area for the climatic conditions of Florence, selected by orientation and position of the window with respect to the wire of the façade

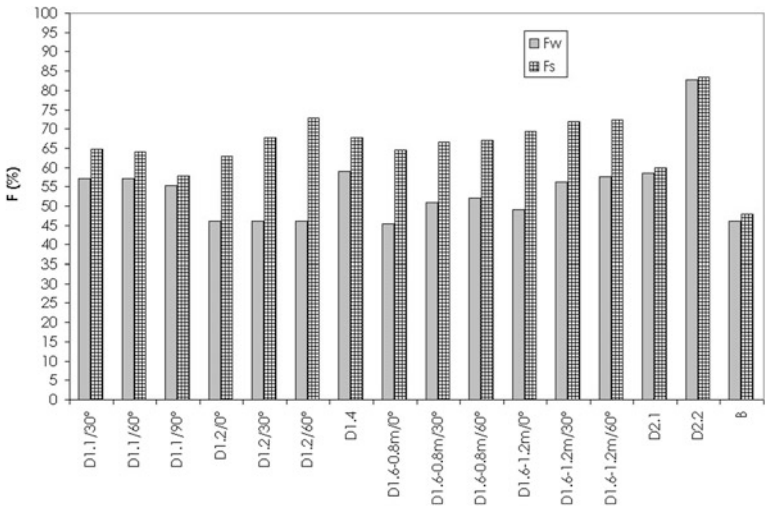


Fig. 23 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Milan, South orientation

orientation) and 59 % (West orientation) and an increase in summer solar gains between 44 % (North orientation) and 80 % (South orientation).

The different position of the frame, relatively to the façade profile, leads to the resolution of some technological details, which concerns mainly the relation with the thermal insulation, the reduction in thermal bridges, the presence or the absence of space where to place the shading system, and the proper sealing on the frame/masonry coupling in order to prevent infiltration of air and noise.

The legislative developments of recent years have given great importance to the need for solar radiation control in summer conditions, forcing the designer to consider the problem of verifying the risk of indoor overheating due to unshielded glass surfaces.

In the absence of effective solar radiation shielding, some refurbishment actions on the existing buildings, such as the reduction in the opaque envelope thermal transmittance, may even increase, rather than decrease, the need for air-conditioning systems in summer and get worse conditions of indoor thermal comfort.

The use of different types of solar shading or glass with solar control can improve the performance of the system window—shading [1, 6, 8], ensuring adequate indoor comfort conditions in both summer and winter and reduction in energy consumption for climate control of the building.

Since shading systems usually are not placed on the North façade, the results from dynamic simulations are compared for South and West façades (the most critical in the summer), resulting from the application of the solar radiation control systems most commonly used in residential buildings, excluding intrusive or hardly feasible configurations.

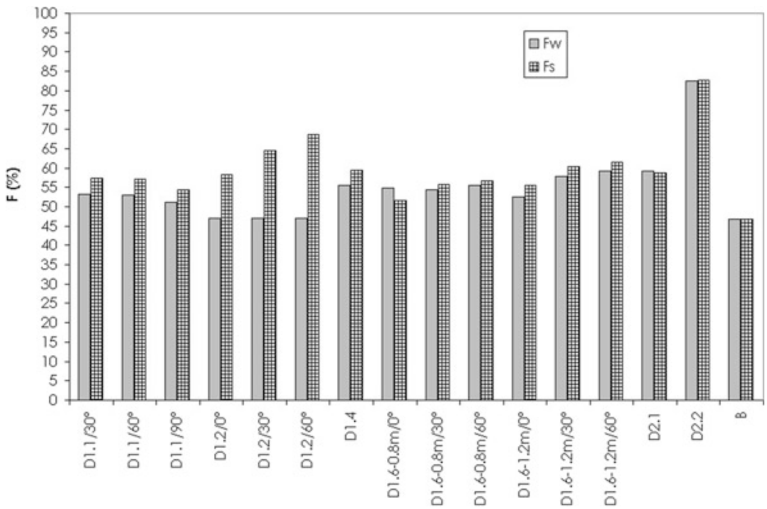


Fig. 24 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Milan, West orientation

The effect of reduction on solar gains was evaluated through the seasonal reduction factor, respectively, in winter (F_w) or in summer (F_s), expressed as a percentage.

In Figs. 23, 24, 25, 26, 27, and 28, relative to the location of analysis, the seasonal reduction factors derived from the comparison with the existing building (phase A) are shown referred to South and West exposure in the various locations; in particular, the D1.2 shading system was considered packaged in the winter season, in agreement with the most common use.

In general, among the several relevant parameters for the choice of a control system of the solar radiation, the capability of the shading system to reduce thermal loads in summer and at the same time to allow solar gains in winter must be taken into account.

This feature can be analyzed by comparing the difference between F_s and F_w (ΔF) extrapolated from Figs. 23, 24, 25, 26, 27, and 28; in substance, a shading system may be considered much more effective if it has a high value of F_s and a corresponding low value of F_w, and then, higher ΔF value corresponds to greater shading effectiveness.

For all the analyzed locations, representative of the different European climate conditions, the values of ΔF were evaluated for the South facing.

The results highlight that the Venetian blind (D1.2) is the most efficient system, when it is considered completely packed in winter; in particular, the blinds tilted to 60° are the most effective. To ensure these benefits, combining this shading system with a building automation system that manages the opening in a dynamic way might be useful.

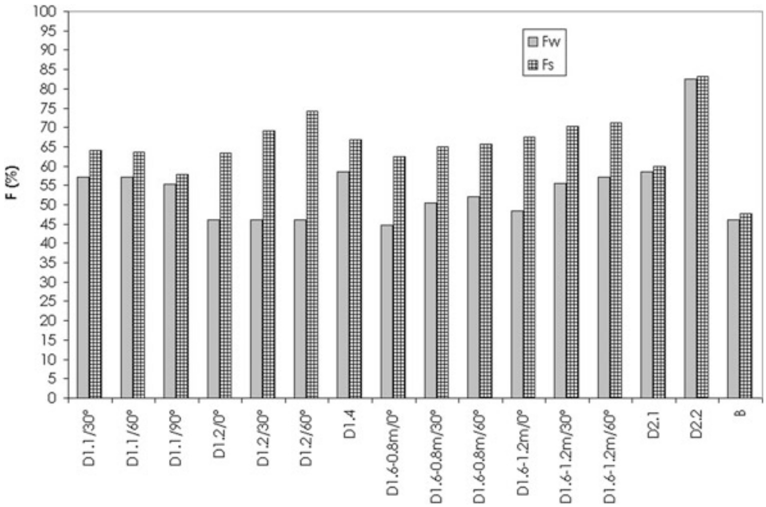


Fig. 25 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Florence, South orientation

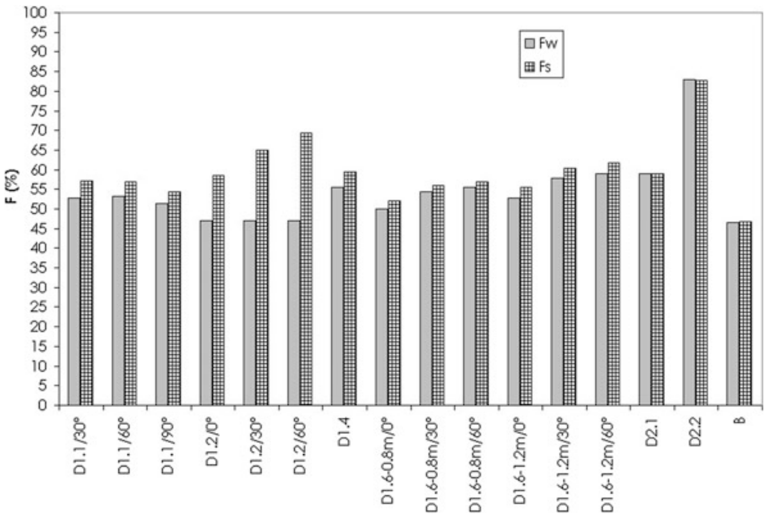


Fig. 26 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Florence, West orientation

The insertion of a shading system (D1.6) in an existing balcony or the addition of a new balcony adjacent to the existing building gives good results, especially when it is combined with horizontal blinds tilted to 0°. In this case, the depth of the balcony (analyzed between the dimensions of 0.8 and 1.2 m) affects in a limited manner.

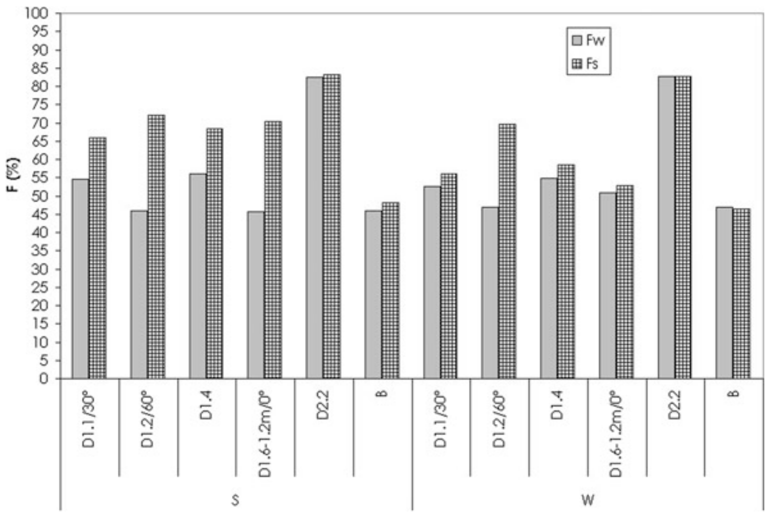


Fig. 27 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Berlin, South and West orientations

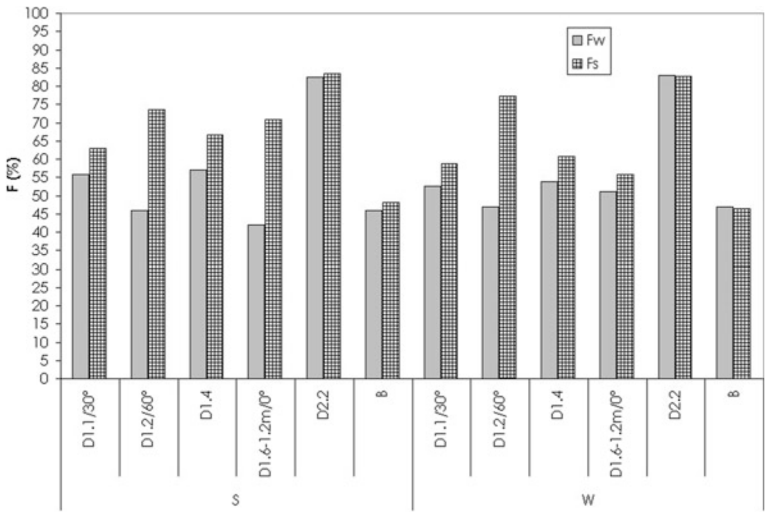


Fig. 28 Seasonal reduction factors (F_w and F_s) for different shading systems selected for Athens, South and West orientations

The shading system perpendicular to the façade with horizontal blinds (D1.1) and the opaque horizontal overhang (D1.4) have very similar performance and far lower than previous analyzed (on the order of 50 %). In particular, the D1.1 typology achieves the best performance for blinds tilted to 30°.

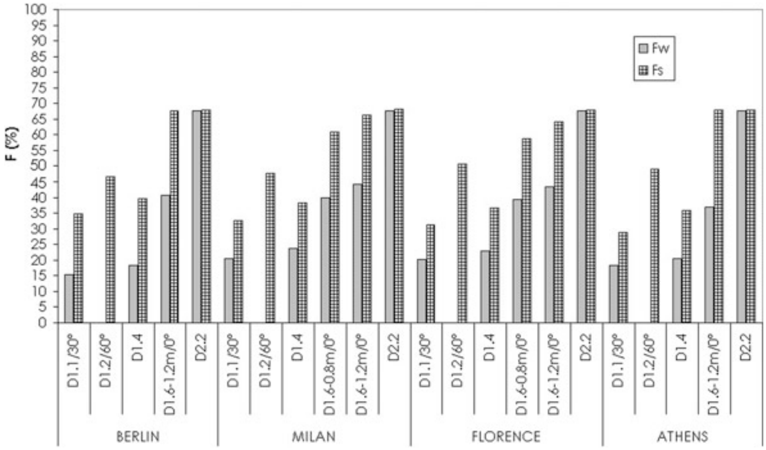


Fig. 29 Seasonal reduction factors (F_w and F_s) for different shading systems, relatively to South orientation

The solar control glasses have the same solar gain reduction, both in summer and in winter, so their use should also be evaluated as a function of the intended use of the property. This strategy can be considered a valuable alternative to the use of external shielding in situations in which the insertion in the façade of extraneous elements to the original morphology of the building is problematic (such as, for example, in the case of historical buildings and in historical centers) or technically complex.

Regarding the West-facing position, the most effective shading system would have vertical blades or blinds, which, however, are rarely used in residential applications. Among the analyzed sunshades, which have in general a lack of effectiveness for this orientation, the external Venetian blind (D1.2) with an inclination of 60° is the most performing.

In Fig. 29, related to South exposure, relative to the locations of analysis, the seasonal reduction factors of the main sunshades that are reported are compared with the replacement of the window (phase B).

This comparison is useful when the designer has already started a process of energy retrofit of the building envelope. This phase can then be seen as a further implementation of the performance, in order to contain energy consumption and improve indoor comfort in summer conditions.

The arising considerations confirm the effectiveness of the analyzed screens for South-facing position and emphasize the highly efficient behavior of the external Venetian (D1.2), the configuration with balcony and integrated shield (D1.6), the sunshade perpendicular to the façade with horizontal blinds (D1.1), and the horizontal overhang (D1.4).

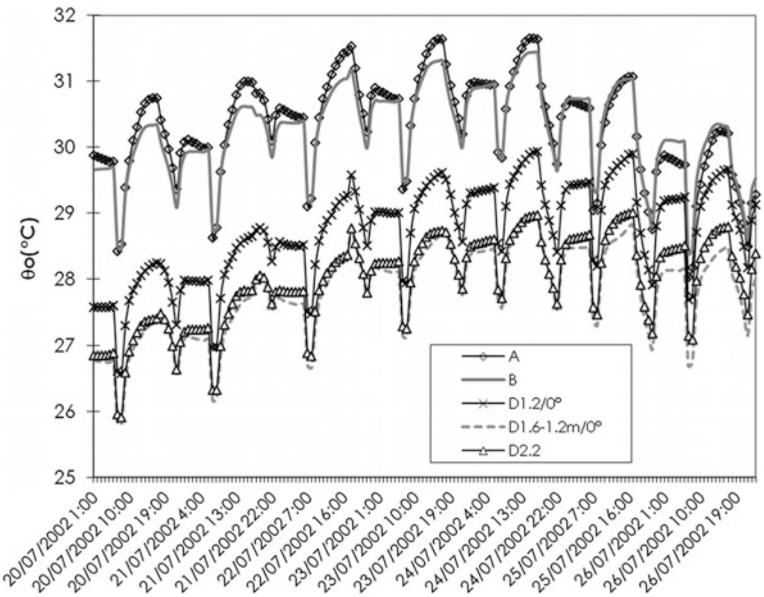


Fig. 30 Operative temperature trend within the South-facing cell located in Florence for different sunshade systems in a typical summer week

It is apparent that the seasonal reduction factors cannot be the only parameters that influence the shading design process, since they do not take into consideration a number of fundamental questions, such as user's comfort, cost, TF of the intervention, and the morphological integration with the building, which will be discussed later.

In particular, the thermal comfort of the occupants can also be estimated by means of the operative temperature. In order to assess, although in a preliminary manner, the implications on the thermal comfort of some solar control systems, Fig. 30 shows the trend of the operative temperature inside the cell type exposed to the South, represented in a summer week (July 20–26) for the location of Florence, while Fig. 31 shows details related to the 23 and 24 of July.

The values for the following configurations are compared: existing building (phase A), replacing windows (phase B), insertion of different sunshade, composed by external Venetian blinds with an angle of 0° (phase D1.2/0°), shielding system integrated on the 1.2-m balcony and blinds with an angle of 0° (phase D1.6–1.2 m/0°), and solar control glass with $g = 0.21$ (phase D2.2).

The simple replacement of the window reduces by little the operative temperature, while the application of screening systems produces a reduction in the operative temperature ranging from 2 °C (with Venetian blinds) to about 3 °C (with integrated system on the balcony).

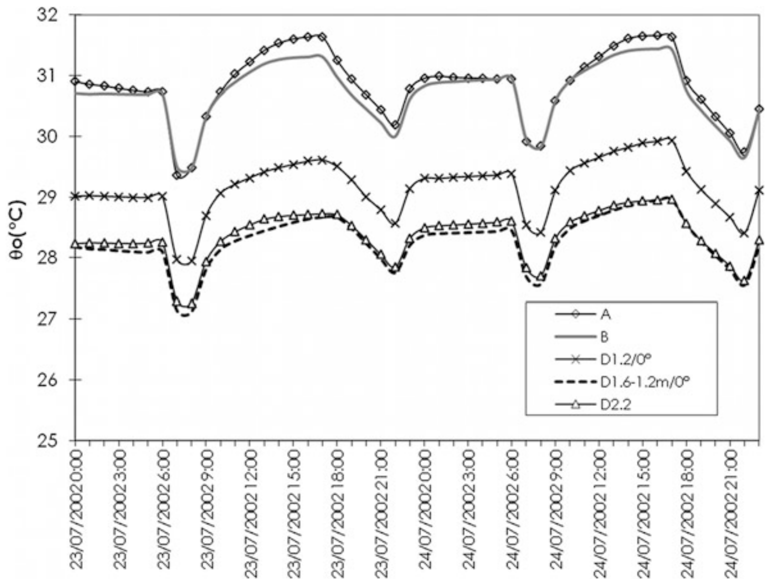


Fig. 31 Detail of the operative temperature trend within the South-facing cell located in Florence for different sunshade systems

The use of solar control glass leads to operative temperature values comparable with those of the integrated balcony systems, proving its effectiveness in summer time, subject to the risk of penalization during winter.

In general, the use of sunshade systems as passive control techniques of the indoor conditions involves both an improved comfort and a reduction in the air-conditioning need in summer season.

6.3 The Shading Effect on Visual and Acoustic Comfort

The windows and the shielding system performances may change significantly both the distribution of daylight, and the thermal and acoustic comfort. Below, the influence on visual and acoustic comfort of different configurations of windows and shielding is described.

6.3.1 The Influence of Shadings on Daylight Distribution and Visual Comfort

The natural light simulations are referred to the systems A, B, C (B and C are equal for this purpose) and D, with the calculation assumptions specified in Sect. 6.1 and using the software RELUX.

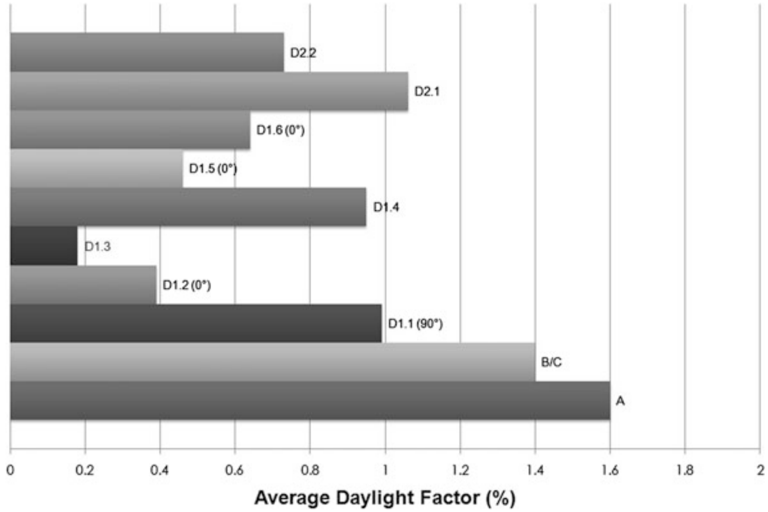


Fig. 32 Average daylight factor with standard overcast sky (*numbers in parentheses* indicate the tilt of the slats)

The influence of different shielding systems and of the kind of glass on the quantity and quality of daylighting has been assessed with reference to different orientations of the façade. The North orientation has been omitted, because it is assumed that on this side, there are no shielding systems. Results referring to East and West are averaged because of their little difference.

The performance evaluation of the different systems is based on the following parameters, already described in Sect. 6.1:

DF Average daylight factor (with standard overcast sky) (%);
UDI Useful daylight illuminance (–);
$E_{\min}/E_m$ Daylight uniformity (with standard clear sky) (–).

The results related to shielding systems D1.5 and D1.6 are referred to a balcony 1.2 m deep.

Figure 32 shows the average DF values for different shielding systems. The analyzed shielding, under overcast sky conditions, significantly reduces the level of natural lighting inside the examined room.

For South exposure, nevertheless they guarantee the maintenance of a good level of natural lighting, as shown in the graph of UDI (Fig. 33).

Almost all the examined shieldings provide illumination levels between 100 and 2,000 lux, more than 80 % of the time during the year, for Southern exposure (Fig. 33). With West or East exposure, shielding types D1.2 and D1.5 guarantee the requirement for 50 % of the time. The remaining time, UDI is less than 100 lux. These shields, if not adjustable, are therefore excessively unfavorable for exposures other than that of South.

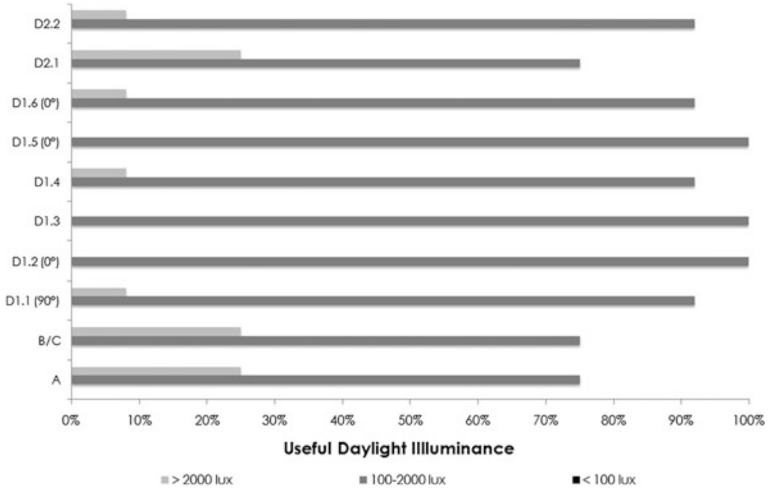


Fig. 33 South façade useful daylight illuminance (*UDI*)

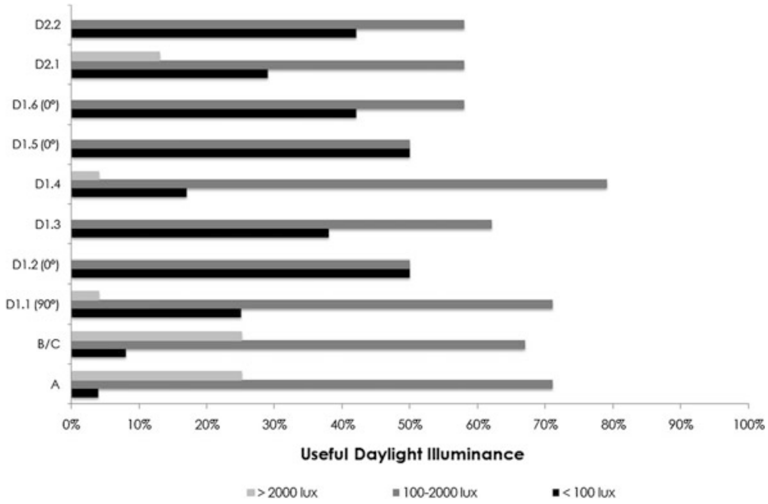


Fig. 34 East and West façades useful daylight illuminance

Figures 32, 33, and 34 show that the systems with inclined blades (D1.2 and D1.3) cause an excessive reduction in the natural lighting level with overcast skies. Therefore, these screens should always be equipped with a mechanism for adjusting the slat inclination. However, with clear skies, they allow a reasonable level of daylighting especially for South-exposed façades, even with fixed and inclined slats.

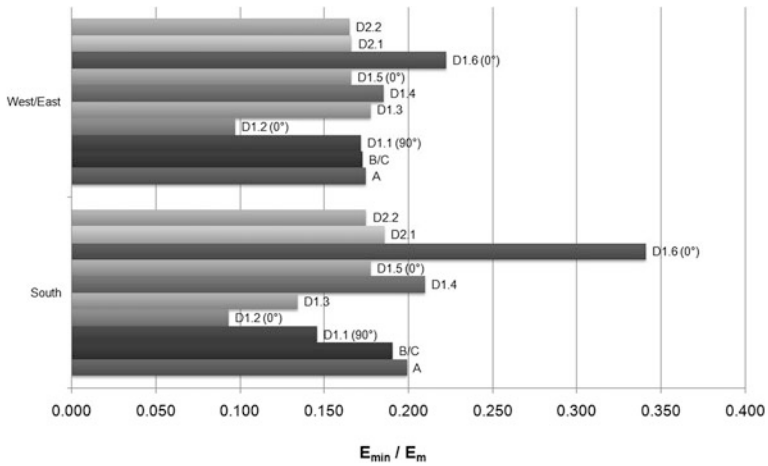


Fig. 35 Uniformity of natural light estimated in clear sky conditions

The shielding system D1.6 represents a good compromise for Visual comfort as it ensures a natural lighting level with clear sky sufficient for most visual tasks for more than 90 % of the time for South exposure and about 60 % of the time for East or West exposure. In addition, the distribution of natural light with clear sky is significantly improved.

The solar control glasses (D2.1 and D2.2), when exposed to South (Fig. 33), are not always appropriate because they can determine internal lighting values that produce visual or thermal discomfort at certain times of the day. For the East or West (Fig. 34) exposure, in certain periods, the natural light must be integrated with the artificial to have a sufficient internal lighting level.

6.3.2 Improvement in Façade Acoustic Performance Due to Shielding Systems

The sunscreens, if well designed, can work as acoustic screens, therefore improving the performance of the façade, ensure significant noise protection of the interior, even with the open windows.

For this purpose, it is necessary that the size and the inclination of the blades of the sunscreens are suitable to intercept all the sound waves coming from the external sources.

In the case of buildings faced to streets, these sources are usually represented by the traffic and therefore are placed at the street level. In these conditions, the horizontal arrangement of the slats reflects the sound waves before reaching the plane of the façade. Therefore, if the lower surface of the blades is coated or made with highly sound-absorbing material, the sound waves are heavily attenuated during reflection, before arriving to the façade (Fig. 36).

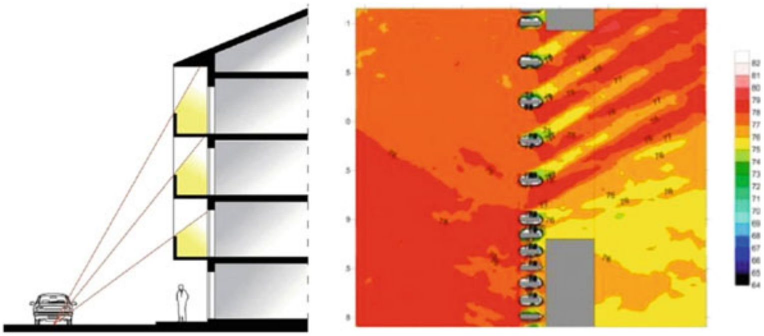


Fig. 36 Effect of a sunscreen of a façade on the sound waves coming from the street. On the right, the detail of the sound level attenuation

In addition, to further increase the effect of sound attenuation, even the surface of the balconies that looks down should be coated with highly absorbing materials.

In order to evaluate the screening effect on the sound pressure reduction in front of buildings, the following parameters are considered, as defined in the standard EN 12354-3 [24]:

$D_{2m,n\mathrm{Tw}}$ Standardized façade sound level difference (dB);
ΔL_{fs} Façade shape level difference (dB).

The acoustic simulations, performed with the software DISIA [11], allow to analyze the acoustic performance of the upper floors façade. The ground floor, in fact, is merely influenced by the screen effect, because the sound waves coming from the road are directed perpendicular to the façade and the shielding effect of the window sills and of screening system becomes therefore negligible.

For the purposes of the simulations, the sound source, which represents the sound spectrum of the urban road traffic, was placed at the center of the roadway in front of the examined façade.

The effect of shielding types D1.1, D1.2, D1.3, D1.4, D2.1, and D2.2 is negligible on the acoustic insulation of the façade, because in these cases, the sound waves cannot be effectively intercepted and absorbed before reaching the façade.

Therefore, the results are referred only to the shielding types D1.5 and D1.6, with different depths of the balcony.

In Fig. 37, the values of ΔL_{fs} at different floors are presented. Numbers after the code of the system indicate the depth of the balcony.

Figure 38 shows the $D_{2m,n\mathrm{Tw}}$ values obtained at different floor levels by applying the proposed methodology. The types A and B, which refer to the façade without screening systems, with basic window (window $R_w = 26$ dB) and upgraded window (window $R_w = 32$ dB), are shown for comparison.

Furthermore, the results also take account of the fact that the application of shielding systems D1.5 and D1.6 involves the replacement of the window with a window door and therefore of the difference in size (1.95 vs. 2.75 m^2).

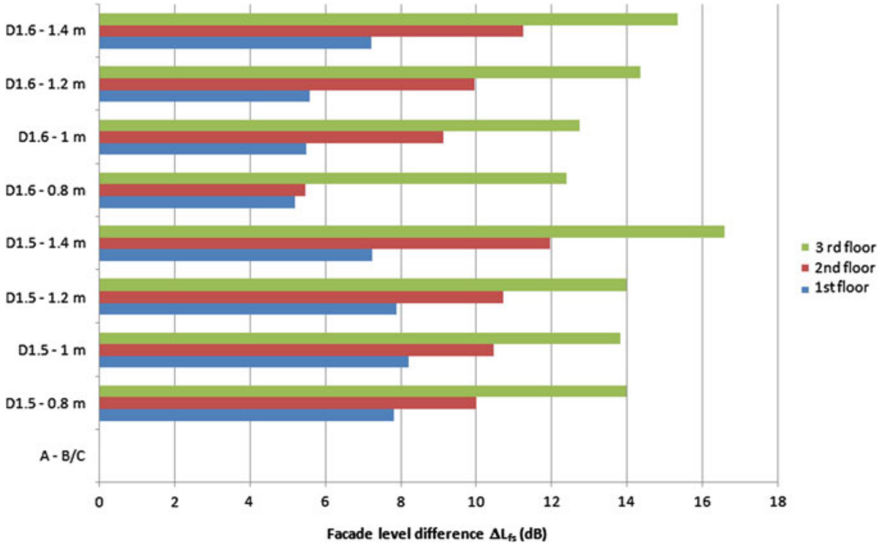


Fig. 37 Sound pressure level differences based on façade shape (ΔL_{fs})

The values referred to the first, second, and third floors are due to the different effectiveness of the shielding, as a consequence of the different angle of incidence of the sound waves, coming from road traffic. This effect is confirmed by the computational method values performed according to the EN 12354-3:2000 (variability in function of the height from the sound source) and by recent studies conducted by the authors [5].

The results demonstrate a strong increase in the sound insulation of the façade, especially at higher floor levels and with screening systems of type D1.5, with sound-absorbing materials built in terraces and louvres. This acoustic effect is particularly significant because it involves an improvement in acoustic comfort in the indoor environment, even in the condition of open windows.

7 How to Choose a Solar Shading Device

In this paragraph, a comprehensive evaluation of the aspects of energy consumption, natural lighting, acoustic comfort, and Technical Feasibility is carried out in the form of a summary.

In particular, the following main functional benefits are evaluated:

- solar gain reduction in summer;
- thermal winter solar gains;
- summer thermal comfort improvement by controlling the phenomena of radiative heat exchange;

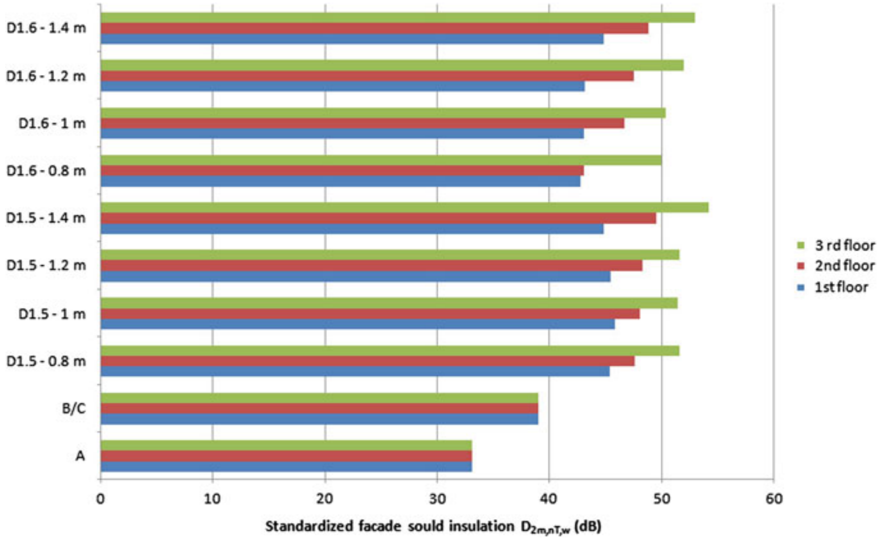


Fig. 38 Façade sound insulation ($D_{2m,nT,w}$)

- Visual Comfort by controlling glare effects, while maintaining the necessary contact with the outside perception in all seasons;
- acoustic comfort improvement;
- thermal resistance improvement in the combination frame/screen, when necessary.

7.1 Selection Criteria

The scheme of shielding typologies in relation to the achievable benefits, starting from the position of the shielding system, with respect to the window (external, internal, and intermediate), takes into account the main functional and performance benefits previously described (Table 6). The third type is widely used in office buildings and for double skin façades [15].

One of the targets of residential building refurbishment is to achieve the above-listed functional benefits; however, mainly due to structural and economic difficulties, external solar shadings are preferred, mainly in the areas with high levels of solar radiation (Mediterranean climate).

Table 7 shows the main types of solar shading systems for residential buildings, sorted according to their position relative to the window. Data are referred to current production, so variations are possible in terms of size and materials related to technological development in the sector.

Table 6 Functional benefits of solar shading with respect to its position

Position	Summer thermal gains	Winter thermal gains	Summer thermal comfort	Visual comfort	Acoustic comfort
External	++	−	++	+	+
Intermediate	+	+	+	+	−
Internal	−	++	−	+	−

Legend
++ Very favorable effect
+ Positive effect
− No effect or potentially negative effect

In Table 8, the different types of solar shadings described in the previous table are summarized, in order to provide preliminary guidelines on the most suitable types for each specific case [15].

In Table 9, the major aspects to be taken into account for the most appropriate screening system and the corresponding actions are reported.

7.2 *Comparative Analysis*

In order to choose correctly a solar shading system, a global comparative analysis has to be carried out.

The aim of this analysis is to define a method for the comprehensive evaluation of the shielding system, previously selected on the basis of the simulations carried out to assess their energy, acoustic, and lighting performance, besides Technical Feasibility and management problems.

This method is applied to the described case study and reported for typical sun-shading devices used in residential buildings.

These considerations are reported in the following data sheets (Table 10), consisting of the following sections:

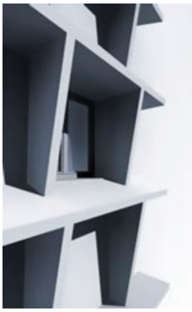
- name of the system;
- technological details;
- analysis of the energy, daylighting, and acoustic behavior;
- synthetic solar shading evaluation.

The analyses of the energy, daylighting, and acoustic behavior were conducted for an unobstructed building, sited in Central Italy (Florence).

Results reported in data sheet concern the comparison between phase D (introduction of solar systems) and phases B/C (improvement in the envelope thermal performance).

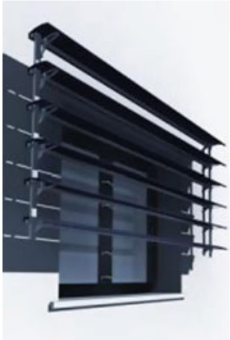
The symbols in the data sheet express qualitative assessments (good, not relevant, or not satisfactory), associated with the screen typology. In particular, they express the relevance of the device in terms of the physical behavior response, with regard to the following requirements and performance indicators:

Table 7 Main types of solar shading systems applicable to residential buildings

Name	Description
External solar shading systems	
Horizontal sunscreen (example D1.1) 	The sunscreen consists of fixed horizontal blinds or grilles anchored to a structure perpendicular to the façade Blind material: extruded aluminum, bent or formed aluminum sheet, PVC-coated copper, wood, glass, PV panels, etc Structure material: aluminum, galvanized steel, etc Blade height (mm): 70–1,500 (with boring) Blade length (mm): max 6,000 Blind step (mm): 70–150
Fixed overhang (example D1.4) 	Overhang fixed horizontal, opaque, made with different materials (sheet metal, treated wood, plastic materials, PV panels, concrete, etc.). Anchored to the wall with an autonomous structure or structurally integrated. The shields may also have a vertical arrangement perpendicular to the façade; in this case, they are most effective for East and West orientations
Grating 	Overhang fixed opaque, made out of different materials, consisting of horizontal and vertical elements to create a grating pattern

(continued)

Table 7 (continued)

Name	Description
Sunscreen fixed blade (example D1.5) 	Outdoor solar shading preoriented blades fixed to the façade. This shading could also have vertical blades; this case, most effective for East/West orientation, is more frequent in commercial building. The blades can also be applied to shield balconies Blade section: ellipsoidal, arcuated, triangular, gull wing, etc Blade materials: extruded aluminum, formed aluminum sheet or bent, wood, PVC, brick, etc Horizontal blade height (mm): 25–1,200 Blade intersection (mm): 70–150 Max length (mm): 8,000
Venetian blinds (example D1.2 and D1.6) 	Solar shield for outdoor use with adjustable and packable blinds. The packaging of the blinds allows a very compact folded element once rolled in. The typology can also be applied to screen balconies other than windows Blind section: arched Blind materials: aluminum alloy, etc Blind supports: steel, etc Blind height (mm): 58–95 Blind width [mm]: 500–4,500 Screen height (mm): 400–5,000 Handling: hand winch crank, home automation systems for solar control
Persian shutter 	The opening of the shutter can be the classic hinged, folding, sliding. The blinds can also be adjustable, allowing good modulation of radiation and light They are applicable in residential buildings, suitable interventions in historical areas Blind material: wood, aluminum, PVC, etc Blind height (mm): 40–150

(continued)

Table 7 (continued)

Name	Description
Roller blind 	Sunscreen with mechanical roller blind. In some models, it is possible to obtain an adjustment of light and ventilation (due to the opening between the blinds). Moreover, it is possible to have the complete obscuration of the interior. It is also a safety guard Material slats: aluminum alloy prefinished, PVC, etc Material structure: aluminum, etc Roller blind height (mm): up to 3,000 Length slats (mm): 500–3,000
Roller curtain 	Sunscreen with mechanical roller curtain Fabrics: glass fiber, acrylic fiber, polyester, PVC, etc Material structure: aluminum, etc Curtain width (mm): up to 7,500 Curtain height (mm): up to 7,500
Sliding arm awning 	This is a combination of the roller curtain and a drop-arm awning, with the fabric dropping vertically and then projecting forward It allows the possibility of having a suitable shielding to solar radiation while allowing ventilation and visual contact with the exterior with lowered curtains
Tent canopy	This kind of sunscreen takes vantage of its convex-shaped canopy giving the possibility of a suitable shielding from solar radiation, while allowing ventilation and the vision of the exterior

(continued)

	A weatherproof casing permits the packing of the canopy Material structure: aluminum, etc Fabrics: opaque screen, waterproof polyacrylic, PVC, etc Overall width (m): 5 Overhang max (m): 2
Drop-arm awning 	Sunscreen with an arm projecting forward when lowered. It is equipped with a fabric and a head box for retracting the fabric It may apply to balconies, uncovered terraces, windows, etc Material structure: aluminum, etc Fabrics: opaque screen, waterproof polyacrylic, PVC, etc Overall width (m): 18 Overhang max (m): 5
Intermediate solar shading systems	
Venetian blind–Roller blind 	Double glazing which integrates into the interior chamber (of variable thickness) a Venetian blind, roller or pleated. The sliding of the tent takes place in a sealed package containing desiccants to ensure the control of humidity and vapor condensation Venetian blind, with respect to roller blind, provides a vision of the outside, even screening down, because it has oriented slats Applicable to windows of commercial and administrative buildings, schools, hospitals, and residences Max dimensions (mm): 32 (pleated and Venetian blinds) Handling: electrical, magnetic mechanism
Internal solar shading systems	
Vertical curtain	Solar shading mostly used to control daylighting, usually operable by hands over a rail system

(continued)

	Panel width (mm): from 660 to 750 depending on the material Rail material: aluminum
Venetian blinds 	Solar shading device composed of slats of aluminum, wood, or plastic that adjusts by rotating from open to closed position by allowing slats to overlap Mostly operated with cord or wand, also available in motorized version. Slats can be perforated This solution is very common in commercial buildings, schools, hospitals, and residential buildings Slat height (mm): 16–75 depending on the material Width and height max (mm): 450

- Technical Feasibility (TF): installation, need for skilled manpower, and need for further building permits;
- Management (M): user’s possibility to act on the effect of the shielding system, for instance by varying the angle of the blinds, easy maintenance, etc;
- Reduction factors F_w, F_s: reduction factors (respectively, for winter and summer and South orientation of the screen) of the solar thermal load, expressed as a percentage. In particular, when F_w is in the order of 20 % or less, the system is considered not affecting the solar gains;
- Visual comfort (VC): takes into account the uniformity of illumination and the amount of available natural light (UDI);
- $D_{2m,n\mathrm{T,w}}$: rating of sound insulation of façade expressed in dB; in particular, it is considered “good” when the contribution of the system is at least greater than 1 dB.

Table 8 Evaluation of different types of solar shadings

Type of solar shading		Summer thermal gains	Winter thermal gains	Winter heat loss reduction	Summer thermal comfort	Visual comfort	Outdoor visual perception	Acoustic comfort	Wind resistance	Best orientation
External position with respect to the frame										
Fixed screens	Horizontal sunscreen	++	++	–	+	+	++	–	++	S
	Fixed overhang	++	++	–	+	+	++	–	++	S
	Grating	++	+	–	+	+	+	–	++	S–E–W
	Horizontal sunscreen fixed blades	++	0	–	++	0	0	–	++	S
	Vertical sunscreen fixed blades	+	0	–	+	0	0	0	++	E–W
Operable shielding	Venetian blinds	++	++	0	++	+	0	0	+	S–E–W
	Persian shutters	++	++	+	++	+	0	+	++	S–E–W
	Roller blinds	++	++	++	+	+	–	+	++	S–E–W
Curtains	Roller curtain	+	++	–	+	0	–	–	0	S–E–W
	Sliding arm awning	+	++	–	+	0	0	–	0	S–E–W
	Tent canopy	+	++	–	0	0	++	–	0	S–E–W
	Drop-arm awning	+	++	–	+	0	+	–	0	S
Position in the cavity of the double glazing and solar control glass										
Venetian blind	0	++	–	0	+	0	–	–	S–E–W	
Roller blind	0	++	–	0	0	–	–	–	S–E–W	
Solar control glass	++	–	–	++	0	++	–	–	S-E-W	

(continued)

Table 8 (continued)

Type of solar shading		Summer thermal gains	Winter thermal gains	Winter heat loss reduction	Summer thermal comfort	Visual comfort	Outdoor visual perception	Acoustic comfort	Wind resistance	Best orientation
Inner position with respect to the window frame										
Vertical curtain	–	++	–	–	0	–	–	–	–	
Venetian blind	–	++	–	–	+	0	–	–	–	

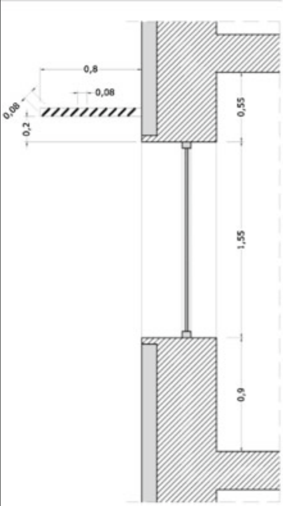
Legend
++ Excellent
+ Good
0 Moderate
– Not relevant
E East, *W* West, *S* South

Table 9 Main aspects to consider for a proper solar shading system choice

Aspects to take into account	Corresponding specific actions
Purposes of the intervention	Solar radiation and summer heat load control, glare reduction, aesthetic and functional rehabilitation, greenhouse effects' control, thermal and acoustic comfort improvement, etc
Historical buildings and landscape	A predetermined choice of shielding systems can be imposed, according to the historic features of the building and the site
Climatic location	Parameter collection and acquisition of the climatic conditions of the site (temperature, solar radiation, prevailing winds, etc.)
Window orientation	Seasonal variation evaluation of the incidence of solar radiation in relation to the environment (presence of shadows, boundary conditions, albedo effect, etc.)
Position on the façade	Position of the elevation of the screen in relation to solar energy and acoustic pressure, winds action, etc
Choice of the shielding system	Type (fixed or mobile), arrangement (horizontal or vertical), and tilt of the flaps, blinds, blades of the screen. Thermal comfort, light, and acoustic performances of the sunscreen
Technical feasibility	Building typology and compatibility with the chosen system: appropriate anchoring techniques, assembly and installation, etc
Management	Management and possibilities of operation, user friendliness, etc
Costs	Cost analysis, comprehensive of the installation
Costs of maintenance	Maintenance cost analysis, easiness to replace, availability of materials and spare parts, skilled manpower, etc
Costs/performances analysis	Costs/performance final evaluation, taking into account all the aspects above examined

Acknowledgments Authors thank Lorenzo Giorgi, Elisa Nannipieri and Leone Pierangioli for the valuable scientific collaboration in the drafting of this chapter.

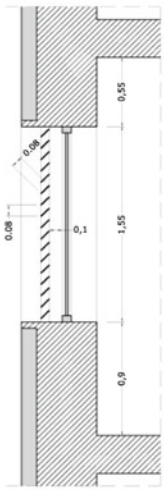
Table 10 Data sheet for different solar shading devices—synthetic comparative evaluation



D1.1 - Sunshade with continuous horizontal blinds (tilting: 30°, 60°, 90°)
Best energy performances for south orientation and 30° blind tilting: Fs = 30% and Fw = 20%. Adequate daylighting. If west/east oriented, basic visual tasks are not guaranteed for the 30% of the year.
This shading does not affect the sound insulation of the façade.

Synthetic Solar Shading Evaluation

TF	M	F_w	F_s	VC	$D_{2m,nT,w}$
🙂	☹	😐	🙂	🙂	😐



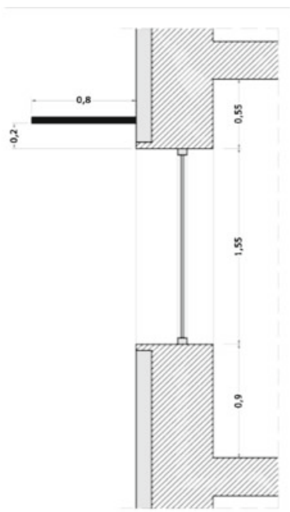
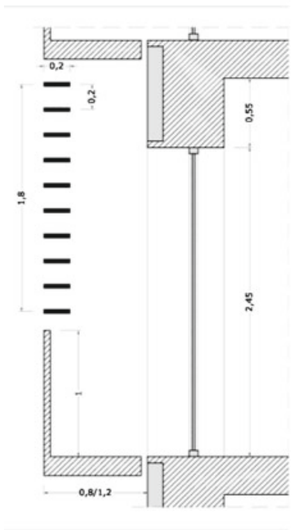
D1.2 - Venetian Blinds (tilting: 0°, 30°, 60°)
Best energy performances for 60° blind tilting: F_s = 47% for south orientation and 44% for west orientation. For every orientation F_w is negligible due to top packaging capability into a very small space.
Adequate light distribution is guaranteed only with south orientation.
This shading does not affect the sound insulation of the façade.

Synthetic Solar Shading Evaluation

TF	M	F_w	F_s	VC	$D_{2m,nT,w}$
🙂	🙂	🙂	🙂	☹	😐

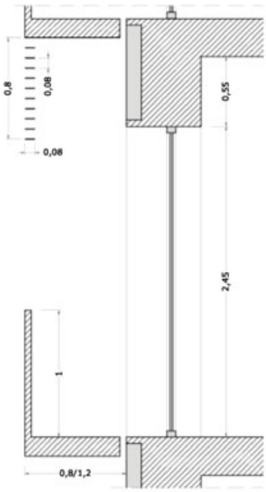
Good	Not relevant	Not satisfactory
🙂	😐	☹

Table 10 (continued)

<table>
<tr><td rowspan="4">
</td><td colspan="6">D1.4 - Overhang opaque fixed horizontal
Best energy performances for south orientation: $F_s = 37\%$ and $F_w = 23\%$. For west/east orientation $F_s = 25\%$ and $F_w = 16\%$.
Adequate light distribution is guaranteed for all the orientations. Visual comfort improves especially in summer.
This shading can negatively affect the sound insulation of the façade as it reflects acoustic waves towards the window.</td></tr>
<tr><td colspan="6">Synthetic Solar Shading Evaluation</td></tr>
<tr><td>TF</td><td>M</td><td>F_w</td><td>F_s</td><td>VC</td><td>$D_{2m,nT,w}$</td></tr>
<tr><td>🙂</td><td>🙁</td><td>😐</td><td>🙂</td><td>🙂</td><td>🙁</td></tr>
<tr><td rowspan="4">
</td><td colspan="6">D1.5 - Sunshade vertical with blades tilted integrated with balcony (tilting: 0°, 30°, 60°)
Best energy performances for south orientation: 0° tilting blades imply $F_s = 77\%$ and $F_w = 65\%$. 30° and 60° tilting blades imply a further Qs_s reduction of 20% and Qs_w of 33%.
Adequate illumination is guaranteed only for south orientation and 0° and 30° tilting blades.
This shading with 0° tilting blades, if realized with sound absorbing material, improves the sound insulation of the façade; this performance increases with the highest floors of the building.</td></tr>
<tr><td colspan="6">Synthetic Solar Shading Evaluation</td></tr>
<tr><td>TF</td><td>M</td><td>F_w</td><td>F_s</td><td>VC</td><td>$D_{2m,nT,w}$</td></tr>
<tr><td>🙁</td><td>🙂</td><td>🙁</td><td>🙂</td><td>😐</td><td>🙂</td></tr>
</table>

Good	Not relevant	Not satisfactory
🙂	😐	🙁

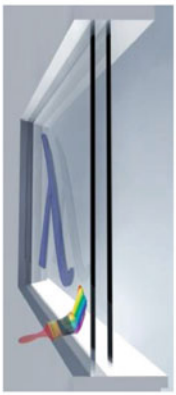
Table 10 (continued)



D1.6 - Sunshade vertical with blinds tilted integrated with balcony (tilting: 0°, 30°, 60°)
Best energy performances for south orientation: 0° tilting blades imply F_s = 64% and F_w = 43%. 30° and 60° tilting blades imply a further Qs_s reduction of 4% and Qs_w of 10%.
Adequate illumination is guaranteed for all the year and different orientations. This shading guarantees a good uniformity of illumination.
This shading with 0° tilting blinds, if realized with sound absorbing material, improves the sound insulation of the façade; this performance increases with the highest floors of the building.

Synthetic Solar Shading Evaluation

TF	M	F_w	F_s	VC	$D_{2m,nT,w}$
☹	☺	☹	☺	☺	☺



D2.1 and D2.2 - Solar control glasses
Energy performances are similar for winter and summer and different orientation as a function of glass solar factor g. For D2.1 F_W = 23% and for D2.2 F_S=68%. Use of solar control glasses can be considered as a proper strategy alternative to external sun shading devices for historical buildings.
Adequate illumination is guaranteed, even if for west/east orientation basic visual tasks are not guarantee for the 30-40% of the year.
Solar glasses can affect the sound insulation of the façade only if Rw of the glass is different from the original.

Synthetic Solar Shading Evaluation

TF	M	F_w		F_s		VC	$D_{2m,nT,w}$
		D2.1	D2.2	D2.1	D2.2		
☺	😐	😐	☹	😐	☺	☺	😐

Good	Not relevant	Not satisfactory
☺	😐	☹

References

1. Baldini S, Carletti C, Cellai G, Nannipieri E, Sciurpi F, Secchi S (2011) Solar radiation control: acoustic and lighting performances of solar shading devices. In: 48th AICARR international congress Baveno, 22–23 Sept
2. Boyce P (1995) Minimum acceptable transmittance of glazing. Lighting Res Technol 27(3):145–152
3. Boyce P, Hunter C, Howlett O (2003) The benefits of daylight through windows. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York
4. Busa L, Cellai G, Secchi S (2005) Acoustic protection of the buildings. Alinea Editore, Florence
5. Busa L, Secchi S, Baldini S (2010) Effect of façade shape for the acoustic protection of buildings. Building Acoustics 17(4):317–338
6. Carletti C, Cellai G, Nannipieri E, Pierangioli L, Sciurpi F, Secchi S (2012) Energy refurbishment of existing buildings with interventions on windows and solar shadings. In: 67th ATI national congress, Trieste, 11–14 Sept
7. Cellai G et al (1994) Energy aspects of windows. In: 49th ATI national congress, Perugia, Italy, pp 271–283
8. Cellai G, Secchi S, Nannipieri E, Baldini S (2011) Acoustic and lighting performances improvement of solar shadings. In: Proceedings of the 38th AIA national congress, Rimini, 8–10 June
9. Cellai G, Secchi S (2009) Evaluating the performance of windows for well-being and reducing energy consumption. In: 47th AICARR international congress system, energy and built environment toward a sustainable comfort, Tivoli (RM) Italy, 8–9 Ottobre, pp 219–230
10. Energy Resources Design (2006) High-performance glazing: making the most of today's advanced technologies. e-News, No. 54
11. Farina A (2000) Validation of the pyramid tracing algorithm for sound propagation outdoors: comparison with experimental measurements and with the ISO/DIS 9613 standards. Adv Eng Softw 31(4):241–250
12. LBNL (US DOE) (2010) EnergyPlus engineering reference, Berkeley, CA, USA
13. Nabil A, Mardaljevic J (2005) Useful daylight factors. Energy Buildings 38(7)
14. Nabil A, Mardaljevic J (2005) Useful daylight illuminance: a new paradigm to access daylight in buildings. Lighting Res Technol 37(1):41–59
15. REHVA (2010) Guidebook n°12. In: Wouter Beck (ed) Solar shading—How to integrate solar shading in sustainable buildings
16. Relux Informatik AG (2007) Relux professional 2007 Manual, Basel, Switzerland. www.relux.ch
17. Russo V (1994) Practical guide-selection and application of special glass insulating. Glass Manufacturers Association

Normative References

18. CIE (1972) Daylighting: international recommendations for the calculation of natural daylight, vol 16. CIE Pub, Paris
19. CIE (1973) Standardization of luminance distribution of clear skies, vol 22. CIE Pub, Paris
20. EN 12207 (1999) Windows and doors—Air permeability—Classification
21. EN 12207 (2000) Windows and doors-permeability-classification
22. EN 12208 (1999) Windows and doors—watertightness—classification
23. EN 12210 (1999) Windows and doors—resistance to wind load—classification
24. EN 12354-3 (2000) Building acoustics—estimation of acoustic performance of buildings from the performance of elements—Part 3: airborne sound insulation against outdoor sound

25. EN 12519 (2004) Windows and pedestrian doors—terminology
26. EN 410 (2000) Glass in building—determination of luminous and solar characteristics of glazing
27. EN ISO 10077-1 (2002) Thermal performance of windows, doors and shutters—calculation of thermal transmittance—simplified method
28. EN ISO 12464-1 (2004) Light and lighting—lighting of work places-indoor work places
29. EN ISO 14683 (2007) Thermal bridges in building construction—linear thermal transmittance—simplified methods and default values
30. UNI 11296 (2009) Acustica—Linee guida per la progettazione, la selezione, l'installazione e il collaudo dei sistemi per la mitigazione ai ricettori del rumore originato da infrastrutture di trasporto (guidelines for the design, selection, installation and testing of systems for the mitigation of noise, originating from transport infrastructure to receptors)
31. Weather data IGDG. http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm