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The role of shading devices to improve thermal and visual comfort in existing glazed buildings

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Abstract

Buildings with large glazed surfaces may show severe thermal and visual discomfort issues, as an effect of the large incoming direct solar radiation. In order to avoid excessive solar gains and glare issues to the occupants, it is necessary to adopt suitable solutions that limit the incoming solar radiation, such as highly reflective coatings or movable shading devices. However, such devices must be accurately selected, according to the building location and to the exposure of the glazed façades, while also taking into account possible regulatory measures. This paper evaluates the effectiveness of a series of shading devices applied to an existing office building in Southern Italy. The building shows large glazed surfaces and has no overhangs, thus significant thermal discomfort is perceived in summer by the occupants. The aim is to identify those solutions that allow to improve thermal comfort while also keeping a sufficient illuminance level indoors, without disregarding the compliance with Italian regulations about the installation of shading devices and, of course, the need to keep costs on a reasonable level. The analyses are repeated for different building orientations, in order to provide general information.

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Keywords: Refurbishment; Apartment block; Mediterranean climate; Passivhaus; Thermal comfort

1. Introduction

The solar radiation admitted through the glazed envelope of a building may have serious effects on thermal and visual comfort in the indoor spaces. Indeed, solar gains heat the indoor spaces, thus significantly contributing to the cooling load in summer; on the other hand, they have a positive effect in winter. Moreover, one should not forget the

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importance of the glazed surfaces for daylighting purposes: actually, if scarce daylight illuminance determines the need to use artificial lighting, excessive and uncontrolled daylight can lead to discomfort issues, mainly related to glare [1]. Hence, the correct management of solar gains is essential, especially in office buildings with large glazed surfaces. In particular, glazed façades facing south or west (in the northern hemisphere) are particularly vulnerable to overheating, inducing thermal discomfort and non-uniform daylight distribution. In these cases, a suitable shading strategy can be helpful to reduce the cooling load due to solar gains, and to improve daylight exploitation [2].

One of the strategies to control solar gains in buildings is the adoption of *smart dynamic glazing* [3]. The term "smart" indicates a glass that can switch its optical properties when needed, triggered by a voltage pulse (electrochromic glazing) or a high temperature (thermochromic glazing). This allows the building shell to be adaptive to climate, i.e. to admit solar energy only if there is a heating or daylight demand [4]. Smart glasses can prevent glare and thermal discomfort, and provide large energy savings for space cooling [1]. However, despite being already on the market, they are not very widespread, also due to their high costs. On the other hand, a *static reflective glazing* can reduce solar gains, but it cannot modify its properties when more incoming radiation is needed.

Finally, movable *shading devices* can suitably be used to control solar gains. Several studies concerning the effectiveness of shading devices in office buildings are available in the literature. As an example, Bellia et al. study the influence of external solar shading devices on the energy requirements of a typical air-conditioned office building (including space heating, space cooling and artificial lighting). The study considers overhangs on the south façade, and louvers on the east-west façades. The simulations are repeated for three different locations in Italy. The results show that, depending on the location and on the building orientation, the adoption of suitable shading devices can reduce the overall energy consumption by up to 24% [5]. In another study, external venetian blinds are identified as the most effective shading device to control heat gains and daylight through fenestrations in office buildings [6].

Atzeri et al. investigate the performance of outdoor and indoor shading devices in an office building located in Italy. Based on thermal and visual comfort, but also on primary energy consumption, their study shows that shading devices may increase the overall energy consumption if not properly conceived, due to the rising heating and lighting needs, while in case of internal shadings even the cooling needs might be penalized [7]. Stazi et al. compare several external solar screens (aluminium sliding perforated panels, aluminium horizontal louvers, aluminium and wooden shutters), taking into account their performance in terms of energy saving, thermal comfort, daylighting and Life Cycle Assessment. Their study, based on experimental measurements and dynamic simulations, suggests that the wooden slats could be a good compromise for the different considered aspects [8]. On the other hand, Freewan looks at the effect of three different outside shading devices (diagonal and vertical fins, egg crate) on thermal and visual performance for an office building in Jordan, with the façade oriented due south-west. He finds out that egg-crate shading devices perform well on a yearly basis, as they block sunrays in hot periods and allow some sunrays to enter in cold periods [9]. Lau et al. find similar conclusions for a high-rise office building in Malaysia [10].

However, the view to outside is another relevant issue when assessing the performance of a shading device. In fact, external horizontal flat or curved louvers may reduce overheating and improve indoor illuminance in offices, but they may also prevent a view to outside. In this case, either perforated louvers or the adoption of a large gap between the louvers may be preferable, even if thermal and visual performance might be penalized [11]. Finally, the adoption of a dynamic control, to modify the position and the slat angle for venetian blinds according to the sun position, is able to optimize daylight utilization in office buildings [12]. In real applications, the interaction of the occupants with roller shades and dimmable electric lights plays a fundamental role, and is not easy to predict [13].

In this paper, an existing office building with large glazed surfaces is considered. The building is located near Palermo, in Southern Italy; due to the high incident solar irradiance, and to the absence of any kind of overhangs, the occupants report pronounced thermal discomfort in summer, unless air-conditioning devices are switched on, which determines a very high electricity consumption. Starting from such a situation, the effectiveness of a series of shading devices is tested, in order to identify those solutions that improve thermal comfort while also keeping a sufficient illuminance level indoors. To this aim, dynamic thermal and daylighting simulations are performed, to calculate the indoor operative temperature, the Intensity of Thermal Discomfort and the illuminance distribution within some representative rooms. The selected solutions comply with Italian regulations about the installation of shading devices and, of course, account for the need to keep costs on a reasonable level. The analyses are repeated for different building orientations, in order to provide general information.

Nomenclature

A	surface (m^2)
E	illuminance (lux)
g	total g-value (glazing + shading device) (-)
ITD	Intensity of Thermal Discomfort (°C h)
n	air change rate (h^{-1})
r	reflectance (-)
s	thickness (mm)
T	temperature (°C)
T_{op}	operative temperature (°C)
U	thermal transmittance (W m^{-2} K^{-1})
τ	transmittance [-]
Subscripts	
sol	solar
vis	visible

2. Methodology

2.1. Summer thermal comfort and summer energy need

In order to measure the thermal discomfort due to overheating in a living space it is necessary to assess how frequently the *room operative temperature* exceeds a threshold value, as well as the extent by which the threshold is exceeded. On this basis, the indicator used in this work to quantify thermal discomfort is the *Intensity of Thermal Discomfort* (ITD), already introduced in a previous work [14]. The ITD can be defined as the time integral, over the occupancy period P, of the positive difference between the current indoor operative temperature (T_{op}) and the upper threshold for comfort (T_{lim}), see Eq. (1):

$$ITD = \int_P \left(T_{op}(\tau) - T_{lim}\right)^+ d\tau \qquad (1)$$

As this study refers to an office building, the occupancy period P corresponds to 9 hours per day, from 09:00 to 18:00. The time profile of the indoor operative temperature in free-running conditions has been determined by means of dynamic simulations performed with Energy Plus. As concerns the threshold temperature, this depends on the thermal comfort theory being adopted. In this work, the authors refer to the *adaptive theory* described in EN 15251 [15]. In this case, the threshold value is not constant in time, but it is updated daily as a function of the mean running outdoor air temperature. In particular, the threshold temperature has been set so as to fulfil Category I introduced by the EN Standard (high level of expectation).

According to the definition reported in Eq. (1), the higher the ITD, the more uncomfortable is a room; on the other hand, if two different shading devices show the same ITD value, this means that they induce the same average thermal comfort, in terms of duration and intensity, over the whole period of occupancy.

Another issue to consider when studying the effectiveness of different shading devices is the possibility to reduce the energy needs for space cooling in the hot season. To this aim, in the dynamic simulations the set point for the indoor air temperature is set to 26°C during occupancy (from 09:00 to 18:00). As a result, Energy Plus calculates the cooling load, i.e. the rate of thermal energy that must be extracted from the building by an ideal cooling system to counterbalance the thermal load, while keeping the desired set-point temperature. The calculation is extended from June to September.

2.2. Daylighting and visual comfort

Shading devices must be accurately selected, since they can potentially yield excessive daylight illuminance reduction. In this case, occupants may find it difficult to accomplish their visual tasks, and the may prefer to switch artificial lighting on, thus increasing electricity consumption. On the other hand, the absence of shading devices may induce glare and visual discomfort.

In order to verify the occurrence of such circumstances, in this paper the daylight illuminance distribution within some representative rooms is calculated by means of the radiance-based tool available on Ecotect Analysis. The illuminance is calculated over a horizontal plane at a height of 80 cm above the floor. The calculation is performed under CIE overcast sky conditions, with a horizontal outdoor illuminance of 10000 lux, and is aimed to verify if sufficient daylight is ensured over the working plane, which means an average illuminance level of at least 500 lux for office buildings [16]. It is also interesting to verify if the illuminance levels exceed 2000 lux in some portions of the working plane, since this condition would suggest the risk of glare [17]. Finally, the illuminance uniformity is verified, based on the Uniformity Ratio, i.e. the ratio of the minimum to the average daylight illuminance over the working plane that, according to EN 12464 [16], should not fall below 0.4 for offices.

3. Case study

3.1. Description of the building

The case study investigated in this paper is an office building located in the city of Catania, a town on the Eastern coast of Sicily, in Southern Italy (latitude 37.5°). Here, the climate is mild in the winter, as witnessed by the low Heating Degree Days (HDD = 833 °C day), defined relative to a base outdoor temperature of 12°C. On the other hand, in the summer the climate is hot, with daily peak outdoor temperatures that may frequently exceed 35°C.

The investigated building shows the same features and problems as a large portion of office buildings, and above all large glazed surfaces without overhangs or fixed shading devices, which results in a good availability of daylight but also causes overheating and thermal discomfort. The building has a parallelepipedic shape, with the long side and the short side measuring respectively 27.5 m and 11.5 m. The main façade is south oriented, and is almost entirely glazed; the north and east façades have only small openings. The offices are distributed over two floors with an identical design: for this reason, only the top floor is simulated, and the intermediate horizontal slab is supposed adiabatic. Each floor hosts nine offices; overall, the building hosts 40 employees.

The outside walls are based on a double-leaf construction, with two layers of hollow clay bricks (100 mm + 80 mm) divided by a 60 mm cavity, and an outer polystyrene layer of 100 mm. The overall thickness, including inner and outer plaster, is 375 mm. The outer plaster has a clear colour; in the simulations, a solar reflectance r = 0.4 is retained. As regards the flat roof, it consists of a frame of steel beams topped by a corrugated metal sheet (3 mm), and a concrete screed to fall (60 mm). The slab has no insulating layer, and the external finishing consists of a bituminous waterproofing membrane (10 mm), whose solar reflectance is r = 0.3. The floor intrados is finished with rigid fiberglass panels (50 mm).

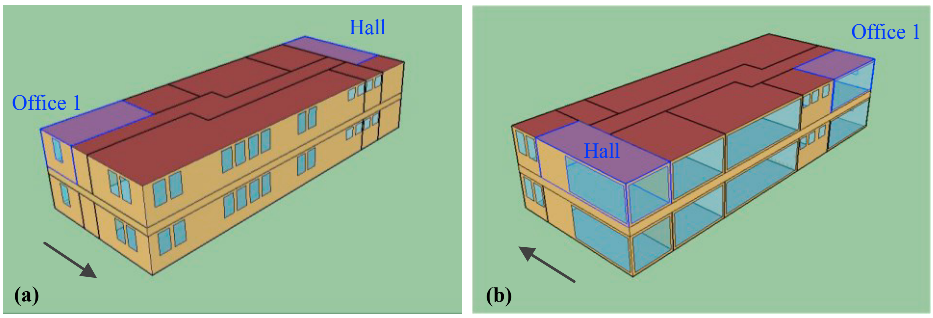


Fig. 1. Model of the investigated building. (a) North and east façades, (b) South and west façades.

The small windows on the north and the east front are provided with single 4-mm glazing with standard thermal emissivity (ε = 0.84), and aluminium frame profiles without thermal break (U_W = 5.7 $W \cdot m^{-2} \cdot K^{-1}$). Instead, the large south and west glazed surfaces are provided with two ordinary glass layers (5 mm) combined with a layer of polyvinyl butyral (1.52 mm). In both cases, the g-value is g = 0.85.

In the simulations, several thermal zones are identified, as shown in Fig. 1; however, only two representative spaces are investigated, namely the entrance hall and the office 1. The building is occupied from 9:00 to 18:00 every day except on Saturday and Sunday. The office occupancy rate is 0.2 person/m^2; the employees perform sedentary activities (100 W sensible load). The power of the lamps is 4 W/m^2 for the offices and 3 W/m^2 for the other spaces zones; computer power consumption (200 W) is also taken into account during office hours. As far as natural ventilation is concerned, a constant rate is considered in the simulations (n = 0.5 h^{-1}), which also includes air infiltration. No mechanical ventilation system is installed. It is useful to remind that in the dynamic simulations the thermostat control for the indoor air temperature is set at 26°C to calculate the cooling energy needs, whereas free-running conditions are considered to calculate the ITD.

3.2. Shading solutions

After assessing the thermal and visual comfort for the building in its current configuration, an additional series of simulations is performed to identify the most suitable shading solutions. In a first stage, twenty-nine different types of shading devices have been considered, belonging to different categories (louvers, curtains, blinds, solar control films). According to UNI 13363-1:2008 [18], different colours (white, pastel and dark), positions (internal, external and integrated into the air gap) and degrees of transparency (opaque, translucent medium, high translucent) have been considered. However, from this first analysis only a few solutions were selected, i.e. those that fully comply with the requisites introduced by national regulations in case of energy retrofit. The selected solutions are:

- external roller blinds (white colour and opaque transparency)
- integrated roller blinds (white colour and opaque transparency)
- external solar control film

However, from a merely economic point of view, integrated roller blinds are discarded owing to their very high costs. Finally, white internal venetian blinds are also considered, as they are the most widespread system thanks to their low purchase and maintenance costs, even if they do not fully comply with national regulations. Table 1 reports the thermo-physical properties of the above-mentioned devices. In the simulations, a control strategy is applied to the shading devices, which are shut when the solar irradiance on the window surface exceeds 200 W/m^2 and the zone air temperature is equal to or higher than 26 °C; this allows taking advantage of the solar gains when needed, and prevents glare occurrence. Of course, such a control strategy does not apply to the solar control film.

Table 1. Properties of the simulated shading devices

	External roller blind	Solar control film		Internal venetian blind
s (mm)	2	0.01	Slat width (mm)	3
τ_{sol} (-)	0.04	0.05	Slat separation (mm)	25
r_{sol} (-)	0.68	0.63	Slat thickness (mm)	0.25
τ_{vis} (-)	0.04	0.08	Slat angle (deg)	45
r_{vis} (-)	0.76	0.61	r_{sol} (-)	0.7
g (-)	0.06	0.15	g (-)	0.26

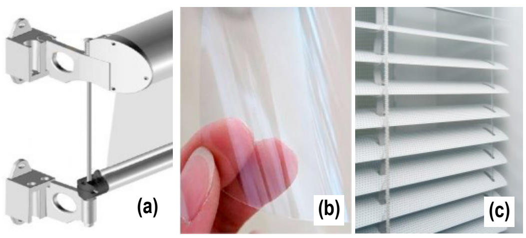


Fig. 2. Examples of the selected shading devices. (a) External roller blinds, (b) Solar control film, (c) Internal venetian blinds

4. Results and discussion

4.1. Thermal comfort

The results of the dynamic simulations in terms of free-running indoor operative temperature are reported in Fig. 3. Here, two different possible orientations are considered: the actual building orientation (with the main glazed façade facing south, as in Fig. 1) and a fictitious situation with the main glazed façade facing west, that is potentially a particularly adverse condition.

The curves reported in Fig. 3 refer to the days showing the highest indoor operative temperatures in summer, namely the 1st of August when the glazed façade faces west, and the 4h of September when the glazed façade faces south. In fact, in September the sun height is lower, which produces higher solar irradiance on south-facing vertical surfaces. Moreover, the curves refer to two different thermal zones (hall and office, see Fig. 1), and to the three selected shading devices. It is here useful to remind that internal venetian blinds represent a reference case, useful for comparison; indeed, it would be very unlikely not to use any – even simple and cheap – solar protection device in a hot and sunny day for a highly glazed building. This option is not even considered in the plots.

Starting from Fig. 3.a, it is interesting to observe that the office shows higher operative temperatures than the hall. This is especially true if less effective shading devices are adopted to block solar gains: indeed, when the main glazed façade is oriented to west, the hall presents one more large glazed surface facing north, which enhances heat dissipation to the outdoors. If one considers the peak indoor operative temperatures in the office, usually attained between 16:00 and 17:00, external roller blinds and solar control film behave similarly, and allow a reduction by about 10°C compared to internal venetian blinds. However, the analysis of the entire daily temperature profile suggests that the solar control film has better performance, especially in the hall, where the temperature constantly keeps around 2°C or 3°C lower than with external roller blinds.

On the other hand, if the main glazed façade is oriented to south, as in Fig. 3.b, the solar control film seems slightly less effective than the roller external blinds. In the office, the difference between the two shading solutions keeps between 2°C and 4°C, and becomes negligible at night. One can also observe that, in the office, the peak indoor operative temperature is usually attained at 13:00, which is common for south oriented spaces. On the other hand, in this orientation the hall also shows a glazed surface oriented to west, which shifts the peak to the afternoon.

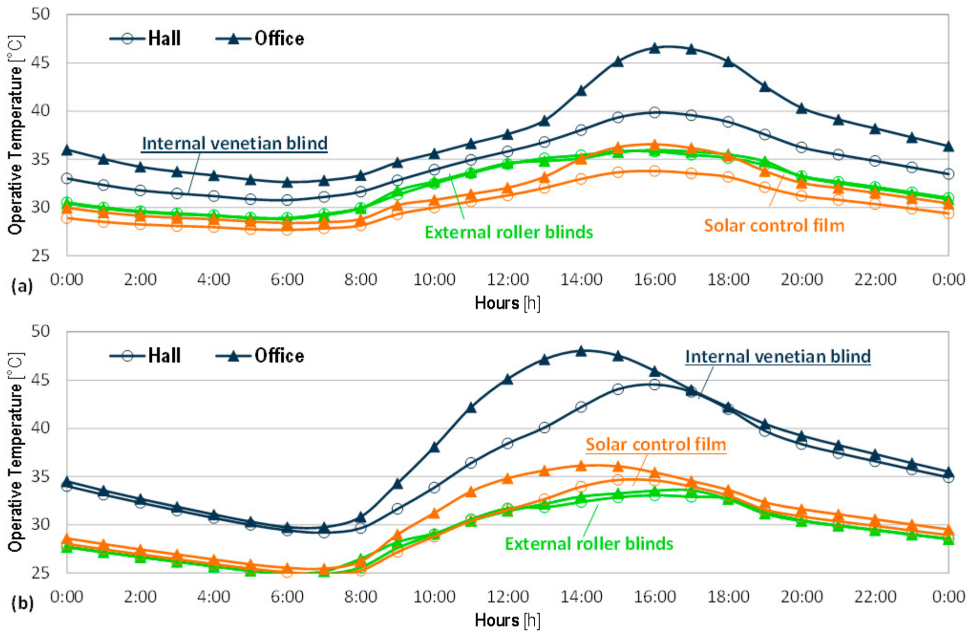


Fig. 3. Operative temperature profiles. (a) West-facing glazed façade (1st August); (b) South-facing glazed façade (4th September)

Now, it is important to highlight that the results shown in Fig. 3 refer just to a specific – and particularly unfavourable – day in summer. However, a most comprehensive investigation should account for the behaviour of the shading devices over a long period, what is possible by considering the ITD.

In this sense, the ITD values reported in Table 2 seem to confirm what has been previously discussed. Indeed, the adoption of solar control films yields better thermal comfort (i.e. lower ITD values) than external roller blinds if the glazed façade is oriented to west, whereas the two technologies show similar ITD values with a south-facing glazed façade, with a slight preference for external roller blind in the offices.

Moreover, Fig. 4 shows the final energy needs for space cooling with reference to the two selected rooms, expressed in kWh per year. In this case, the simulations are carried out by keeping the indoor air temperature at 26°C through a fictitious thermostat control. The energy needs are calculated over the period ranging from the 1st of May to the 31th of October; indeed, it is well known that in highly-glazed buildings the cooling season is longer than just the summer months, and the space cooling system has to be frequently activated in May or October in order to ensure comfortable indoor conditions.

The results reported in Fig. 4 confirm that the best performing solution is the solar control film in case of west-facing glazed façade. In fact, in this case the solar control film allows to save 59.8% thermal energy in comparison with the trivial use of light internal venetian blinds. The adoption of external roller blinds reduces the energy savings to 47.7%. On the other hand, in case of south-facing glazed façade the two devices show similar performance, and the energy savings amount to 60.6% and 59.0% respectively for external roller blinds and solar control film.

The use of light internal venetian blinds contributes to reduce the energy needs if compared to the case without any shading device, but their effectiveness is not outstanding, being the benefits between 12% and 15%, respectively for west-facing and south-facing glazed façades.

Finally, it is useful to remark that, if the energy needs were calculated limited to summer months (from the 1st of June to the 30th of September), the results shown in Fig. 4 would be significantly lower, being the difference between 15% and 25% for internal venetian blinds, and below 10% for the most effective shading devices. This confirms that highly-glazed buildings may suffer from overheating even in mid-seasons (May and October), when the sun height is low and the contribution of the direct solar irradiance to the thermal loads keeps a non-negligible role.

Table 2. ITD values over the cooling season (June – September)

	West-facing glazed façade		South-facing glazed façade	
	Hall	**Office**	**Hall**	**Office**
No shading	5943	9972	8944	9911
Internal venetian blind	5255	8463	7052	7843
External roller blind	3540	3544	2577	2416
Solar control film	1259	2694	2291	2991

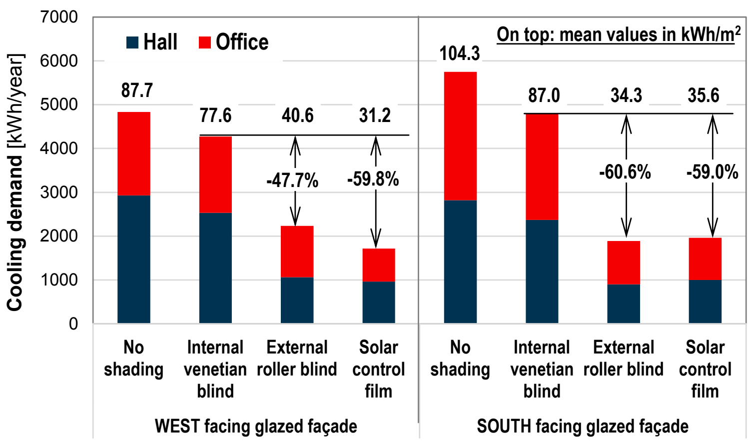


Fig 4. Total final energy demand for space cooling over the cooling season (May – October)

Finally, it is necessary to comment about one more relevant issue, frequently overlooked when discussing about thermal comfort. As highlighted before, the simulations aimed to calculate the final energy needs for the cooling system are carried out by considering a constant indoor air temperature in the conditioned spaces (26 °C). This hypothesis corresponds to a quite common practice in the field of air-conditioning, since the dry bulb air temperature can be easily measured through very widespread and cheap thermostats. However, the degree of thermal comfort perceived by the occupants does not strictly depend on the air temperature, but it depends on the operative temperature, the latter being heavily influenced by the temperature of the surfaces enclosing the indoor space. Hence, it seems interesting to assess the operative temperature perceived by an average occupant placed in the centre of the selected spaces (hall and office) when the thermostat control on the air temperature is set at 26 °C.

The results of this analysis are reported in Fig. 5 for two significant days, with reference to the case with solar control film. Here, it is apparent that the indoor operative temperature diverges significantly from 26 °C, even if an air-conditioning system is in operation. During the sunny hours, solar irradiance penetrates through the large glazed surfaces, heating the floor and the walls; moreover, the glazing itself gets heated. Finally, one must not forget the role of the roof, that collects high solar irradiance and, in this case, is not insulated. Under these circumstances, the operative temperature can even reach 29 °C in the office and 28.5 °C in the hall: as a consequence, the occupants may feel uncomfortable, and may react by lowering the thermostat set-point (e.g. down to 22-23 °C) to counterbalance the radiant heat exchange with the hot surfaces.

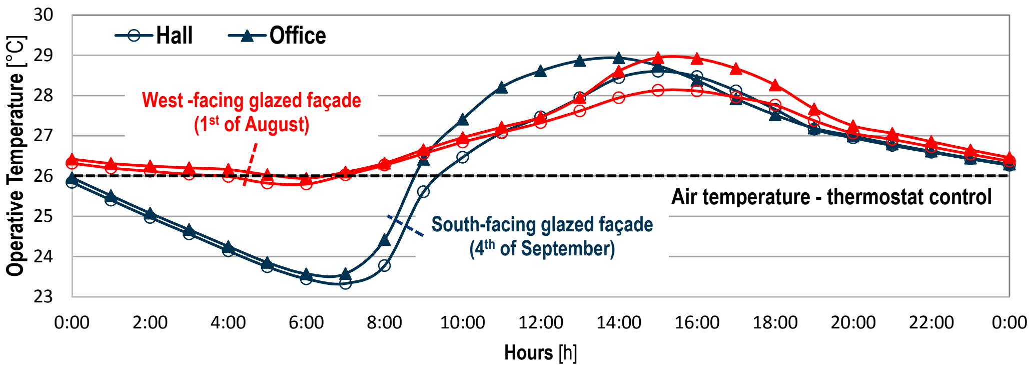


Fig. 5. Operative temperature profile vs indoor temperature with thermostat control (solar control film).

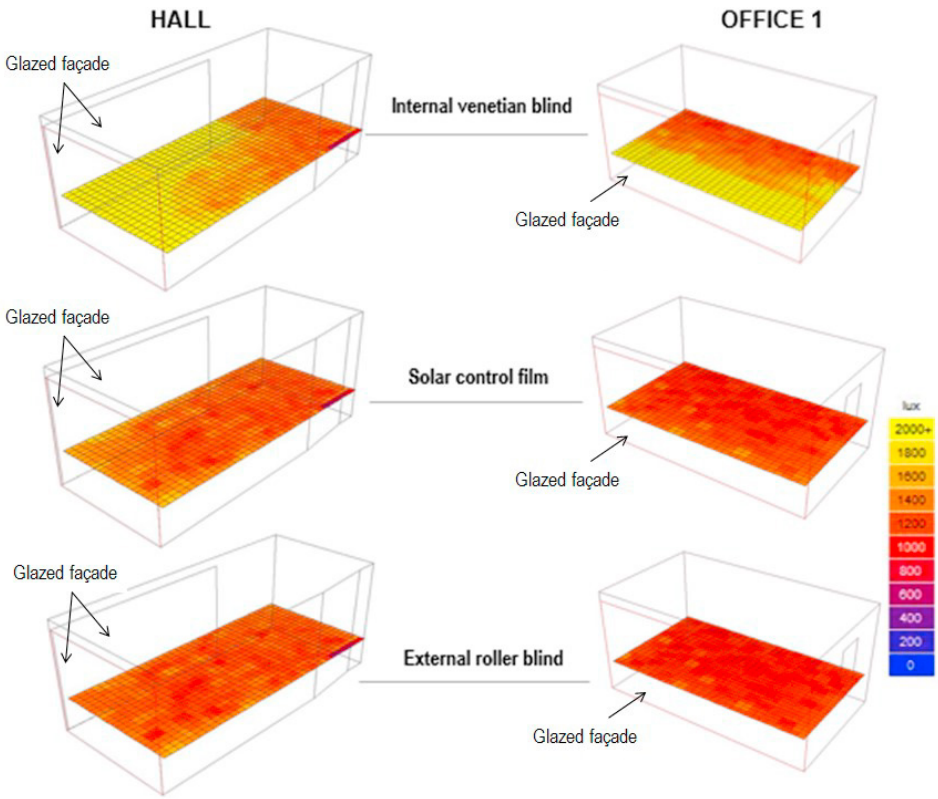
4.2. Visual comfort

The results discussed in Section 4.1 show that the adoption of the selected shading solutions can significantly reduce the energy needs for space cooling in summer, both in the entrance hall and in the office. Moreover, they allow to reduce overheating in case the air conditioning system is not used, thus improving indoor thermal comfort.

However, a possible side effect of the shading devices is an excessive reduction in the daylight availability. This can occur especially if the shading device has a too low visible transmittance, or when the occupants cannot lift it in the event of cloudy sky conditions. This might be the case of the solar control film.

Hence, to verify the occurrence of insufficient daylight, daylight simulations have been performed under CIE overcast sky conditions, and the results are summarized in Fig. 6. As the simulation refers to overcast sky, the orientation is not relevant in this case. The illuminance maps reported in Fig. 6 suggest that sufficient daylight is available in both the hall and the office when the shading devices are shut. External roller blinds and solar control film show very similar results: in the office, the minimum illuminance value is very close to 500 lux (threshold value for offices), but on average the daylight illuminance is above 1100 lux. In this case, the Uniformity Ratio is 0.44, i.e. above the minimum value suggested by EN 12464.

Still looking at the office, it is also interesting to observe that the maximum illuminance value close to the glazed surface keeps below 2000 lux, which suggests the absence of glare. Of course, further analyses should be conducted to evaluate glare occurrence in terms of luminance.



	Illuminance [lux]				Uniformity Ratio [-]	
	Hall		Office		Hall	Office
	Min	Mean	Min	Mean		
Internal venetian blind	1388	1889	653	1671	0.64	0.39
External roller blind	1023	1320	510	1160	0.76	0.44
Solar control film	1018	1261	483	1105	0.79	0.44

Fig. 6. Daylight illuminance distribution and corresponding Uniformity Ratio under CIE overcast sky

As concerns the entrance hall, higher illuminance values are observed, thanks to the presence of a glazed surface on two sides of the room: in this case, the minimum illuminance is around 1000 lux, and the Uniformity Ratio ranges between 0.76 and 0.79. Hence, the hall is very well daylit, which enhances its fruition and provides a sense of connexion to the outdoors. Moreover, once again glare is not likely to occur, since the maximum illuminance keeps slightly below 2000 lux. On the contrary, internal light venetian blinds do not seem as effective as the other shading devices. Indeed, the illuminance on about half the working plane keeps above 2000 lux, both in the office and in the hall. Furthermore, the Uniformity Ratio decreases, and in the office it now gets slightly lower than 0.4. These results suggest that internal venetian blinds, even when shut, provide a non-uniform daylight distribution within the offices, with highly likely risk of glare in the half of the room closer to the glazed façade.

5. Conclusions

The results discussed in this paper show that the adoption of suitable shading devices in highly-glazed office buildings is of the uttermost importance, as it allows to significantly reduce the energy needs for space cooling and to improve thermal comfort while limiting indoor overheating. Moreover, the indoor daylight illuminance keeps suitable levels to allow visual tasks; illuminance distribution is improved and glare risk is considerably reduced.

However, not all the shading devices show the same effectiveness. First, internal blinds should be avoided, since their benefit in terms of comfort is much lower than for external blinds. Then, the results suggest that outer solar control films perform well on all the orientations; on the other hand, external (roller) blinds are very effective on south-facing glazed façades, whereas their performance is worse than solar control films in west-facing glazed façades.

In any case, it is not easy to draw general conclusions. The present study suggests that the design of highly-glazed office buildings must be tackled through dynamic simulations involving both visual and thermal comfort, and must be optimized case by case. Such analyses must not disregard the difference between indoor air temperature and operative temperature, the latter being considerably higher than the former, due to the indoor surface heating induced by the large incoming direct solar radiation. Control logics for space cooling systems should account for this issue, and should not simply operate on fixed set-points on the indoor air temperature.

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