Solar control devices on glazed facades

Optimizing the shape of an outer slat array as function of latitude, climate and solar control strategy

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Abstract: *The arrays of external movable slats are one of the most effective solar control devices on transparent building envelope elements. Furthermore, they significantly affect the image of the building.*

For a south facing glazed façade it is normally assumed that slats with the major axis horizontal are convenient, while for the east and west orientations it is better to arrange their major axis vertically. Therefore, intermediate inclinations should be appropriate for intermediate orientations of the façade.

The optimal shape of a slat array depends on a number of factors such as: visible solar paths, which are defined by the Latitude and orientation of the façade, local climate and building's energy balance; the latter determines the relative weight of energy demand for heating, cooling and artificial lighting. If the slats are equipped with PV cells, the energy balance of the building must also take into account their electricity production.

If the slats are movable and/or combined with other devices, such as internal curtains, any solar control strategy reduces the incoming luminous flux, and this increases the period of use of the lamps, with the necessary consequences on energy demand and comfort. Therefore, the part of the sky that the façade sees through the slats become important, and this depends on the inclination of slats longitudinal axis.

In reference to a typical office room with a fully glazed exterior wall, in a northern Italian climate, in this work is proposed a computer method for finding the optimal slope of the slats longitudinal axis as a function of: local climate, façade orientation and various solar control strategies.

The analysis was performed only by means of computer simulations. With regard to the case study in the examined climate the results show that the optimal arrangement of the slats major axis varies significantly depending on the solar control strategy adopted.

Keywords: Building Energy, Solar Control, comfort

1. INTRODUCTION

External movable slat arrays are one of the most effective solar control devices on transparent building envelope surfaces, particularly on a fully glazed façade. Their shape significantly affects the aesthetics of the building (Figure 1).

If the façade is oriented to the south, it is normally assumed that slats with the major axis horizontal are convenient from an energy and comfort point of view, while in the case of the east and west orientations it is better to arrange their major axis vertically. Therefore, intermediate inclinations should be appropriate for intermediate orientations of the façade. Actually, the optimal shape of a slat array depends on a number of factors such as:

- visible solar paths, defined by latitude and façade orientation,
- local climate, in particular: temperatures and intensity of solar radiation,
- building's energy balance, which is a function of its intended use (time profile of use, internal gains, required Illuminance) and construction technologies of its envelope (which means U-values and thermal capacity),
- weight of energy demand for artificial lighting compared to that for heating, ventilation and air conditioning.
- if the slats are equipped with photovoltaic cells (PV cells), the energy balance of the building must also take into account their electricity production.

If the slats are mobile and/or combined with other devices, such as internal curtains, any solar control strategy reduces the incoming luminous flux, and this increases the period of use of the lamps, with the necessary consequences on energy demand and comfort. Therefore, it becomes important which part of the sky and the external luminous surfaces the façade sees through the slats, and this depends on the inclination of the slats longitudinal axis (their lateral slope).

Figure 1: Example of an office building equipped with an external slat array, in this case, with a horizontal major axis and built-in PV cells, the façade is oriented approximately to the south (building headquarters of the "Citadel of Construction" in Venice, photo by the author)

In reference to a typical office room with an entirely glazed exterior wall in a northern Italian climate, that of Venice (45.5° N, 20 °C-base heating degree-days equal to 2345), in this work is proposed a computer method to find the optimal inclination of the slats longitudinal axis as a function of: local climate, façade orientation and various solar control strategies. The analysis was performed only by means of computer simulations, the results of which are reported here.

The various solutions were evaluated in relation to the total primary energy demand, and their effects on general indoor comfort conditions. The primary energy demand considered is that for heating, ventilation, air conditioning (HVAC) and artificial lighting, since solar control strategies influence these end uses of energy. Furthermore, these end uses of energy are linked to each other; and analyzing them separately can lead to misleading results. For these reason the computer simulations were performed by using a specifically homemade software (Ener_Lux), which simulates the dynamic thermal and luminous behaviour of the room at hourly time steps, and allows simultaneous analysis of energy and comfort issues. The peculiarity of this software, already presented in a previous SET conference (Carbonari, 2017; Carbonari, 2023), is that, within each calculation time step, it calculates thermal and luminous comfort indexes values, on the base of these, it simulates the feedbacks on the solar control devices and/or on the set-point temperatures.

Various possible solar control strategies, aimed at minimizing the energy demand and avoiding glare phenomena, were simulated. One is based only on the use of the slats minor axis slope; another uses in addition to it an internal diffusing curtain. A strategy was also simulated aimed at maximizing the electrical production of photovoltaic cells positioned on the slats, while maintaining visual comfort conditions.

The results of the simulations show that for the case study in the examined climate the optimal arrangement of the slats major axis varies significantly depending on the solar control strategy adopted.

2. THE CASE STUDY

The case study consists in an office room of medium size located in a building with typical structure and glazing. The room dimensions are as follows: 5.88 m wide along the façade, 5.22 m deep orthogonally to it, with internal height equal to 2.70 m (Figure 2). The only external wall of the room is one of the longer, it is entirely glazed with a triple glazing with 0.004, 0.006 and 0.004 m thick glass layers. The air gaps are 0.018 m thick. The inner air gap as a low emissive layer in the external side of the internal glass (overall U_{value}: 1 $W \cdot m^{-2} \cdot K^{-1}$). It is hypothesized that the building has a point structure in beams-pillars in reinforced concrete, with floors in brick concrete 0.3 m thick. The inner walls are in hollow bricks 0.08 m thick with plaster in both sides.

In the energy balance of the room, all the five internal enclosing surfaces have been considered as adiabatic. The thermal capacity relative to a thickness corresponding to half of their total thermal resistance was attributed to each building element bordering the room. In this study, the shading effect of surrounding buildings has not been taken into account.

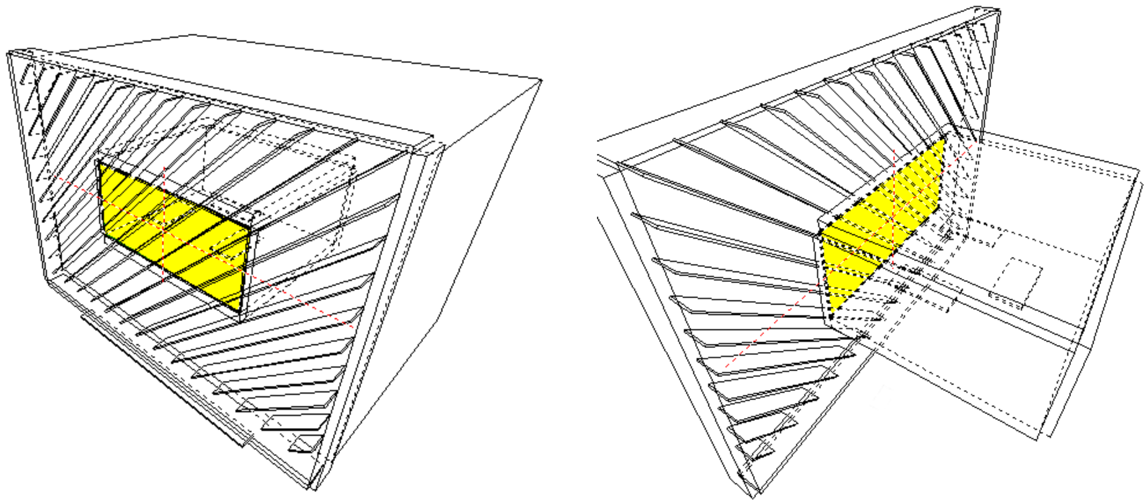

Figure 2: The geometric model of the examined room, in the figure the lateral slope of the slat array is +45 °. The increased extension of the slats and the other shielding elements serve to avoid edge effects

In the office room, the presence of three occupants with the relative equipment have been assumed. Therefore, the internal gains of the room consist of sensible and latent heat flows from occupants (3 people · 65 W of sensible thermal power and 65 W latent), office devices (3 computers and 1 printer for a time average total power equal to 150 W) and a light system consisting of fluorescent lamps (luminous efficacy: 91 lm/W, total power: 250 W). The lighting system is divided into two zones along two bands parallel to the glazed wall. There are no dimmers. The light system is sized to ensure the required illuminance of at least 500 lx, in harmony with Italian regulations for schools and offices. A daily occupation period equal to eleven hours was supposed: from eight in the morning to seven in the afternoon. With these assumptions the thermal load of the room is almost always negative.

The evaluation of the light comfort was carried out only in the hours of complete daylighting with both areas of the lamp set off. Two types of glare were considered here: the disability glare from direct radiation on the visual task, and discomfort glare due to exceeding luminance contrast inside the field of view (Hopkinson, 1963). This last is assessed by means of the Daylighting Glare Index (DGI), in case of extended light sources (Chauvel et al., 1982; UNI, 2000), or Unified Glare Rating (UGR) in case of smaller sources (CIE, 1995). In this study, the first type of glare is considered excessive when the luminance of the task or its irradiated parts exceeds 580 cd/m^2 (Robbins, 1986). It has been assumed that the presence of glare of any kind in one occupant's position entails solar control actions. For the purposes of visual comfort assessments, two lines of sight were considered for each occupant: one towards a visual task placed on the desk, therefore inclined downwards, the other, more critical, is horizontal and directed towards the center of the glass wall.

The glass wall is protected by a system of external slats whose reflection coefficient is equal to 0.6 on both sides, both in the thermal and light range. The slats are 0.6 m wide in the perpendicular direction to the façade (their minor axis) and vertically spaced 0.6 m apart. If the slats are equipped with PV cells, the reflection coefficient of their upper face is assumed to be equal to 0.2. The slats can be tilted around their longitudinal axis and the following solar control logic has been simulated:

- a "seasonal" control logic, according to which the slats are inclined at first in order to minimize the thermal load, but guaranteeing the required level of illuminance even in the most disadvantaged position, after which, if glare problems are detected, an internal diffusing curtain is lowered (its transparency coefficient is 0.5),
- the same seasonal control logic but without internal curtain; in this case the slats, after being inclined so as to minimize the thermal load, can be further inclined to avoid possible glare phenomena,
- if the slats are equipped with PV cells, two control logics has been simulated: one is aimed only at maximizing photovoltaic electricity generation and the other is aimed at doing this while maintaining as much as possible the daylighting in the room; in both cases, if glare phenomena are found, the internal curtain is used.

To calculate the primary energy demand related to HVAC, it is assumed that the building is equipped with a full air centralized loop, the room is used from 8 a.m. to 7 p.m. but the plant is activated at 07 a.m.. In the HVAC system, electrically driven chillers (vapor compression chiller) provide the fluid for the cooling coils, while the fluid for the heating coil is primarily provided by the condensers of the chillers, and an additional gas-boiler intervenes when necessary. The chillers have a nominal Coefficient of Performance (COP) equal to 4.5, while boilers have an efficiency of 0.9. In each calculation step, these values are modified according to the actual load. Internal set-point air temperatures are assumed to be 20°C in winter and 26°C in summer, as prescribed by the Italian law, while in half-seasons they have been assumed equal to the average daytime external temperature, since the clothing of the occupants is adapted to it. The relative humidity set-point is assumed equal to 50% all over the year. The following conversion factors were used to quantify primary energy demand: 1.05 and 2.77 for gas and electricity respectively, in accordance with Italian standards. The second coefficient is the inverse of the efficiency of the national electricity system (i.e. 0.36), the same coefficient was also used to estimate the primary energy equivalent to the possible electricity production of PV cells.

3. RESULTS

3.1. Room’s primary energy demand

Given the assumptions made regarding the intended use and the construction technologies, room’s thermal load is usually negative. Therefore, the annual primary energy demand for heating is minimal, that for cooling is the dominant item followed by that for artificial lighting, which generally is slightly lower.

In the following, the lateral inclination angles that rotate the slats major axis counter clockwise for an observer who looks at them from the outside are defined as positive, negative those that rotate it clockwise.

Since solar control strategies can significantly reduce the incoming luminous flux by significantly influencing energy demand for lamps and consequently for cooling, with a first series of simulations the energy demand of the room was analysed in the absence of any type of solar control, therefore with fixed slats, with minor axis orthogonal to the façade, and without internal curtain.

First, it has been observed that deviating from the south orientation of the glazed surface the total primary energy demand increases going eastwards, and decreases going westwards. This is mainly due to the time of use of the room, which is more extended in the afternoon; therefore, the south-west and west orientations result in lower consumption for artificial lighting and cooling (Figure 3).

While for the south orientation of the façade the horizontal arrangement of the slats is the most convenient, for the other orientations examined it is more convenient a lateral inclination of the slats of about ten sexagesimal degrees, in a positive direction going towards the east and negative going towards the west. In general, positive lateral inclinations are more convenient going eastwards while negative ones are more convenient in a westerly direction. These inclinations, in fact, reduce the incoming solar radiation, in particular its direct component and consequently that reflected by the slats, while there are no significant differences in the sky diffuse component. This reduces the energy demand for cooling, which is the most influential. In fact, in the absence of solar control actions, that can cause the lamps to turn on, there are no significant differences in the energy demand for artificial lighting.

Always in the absence of glare control, fixed slats but with a downward inclination of their outermost edge of thirty degrees were analysed. Understandably, with such inclination the differences between positive and negative lateral inclinations increase.

With the same hypotheses, similar results were found for locations at lower latitudes, i.e. Trapani and Marrakech, or higher, i.e. Berlin. But the differences described above are much less marked for locations further north, where the energy demand for cooling is lower.

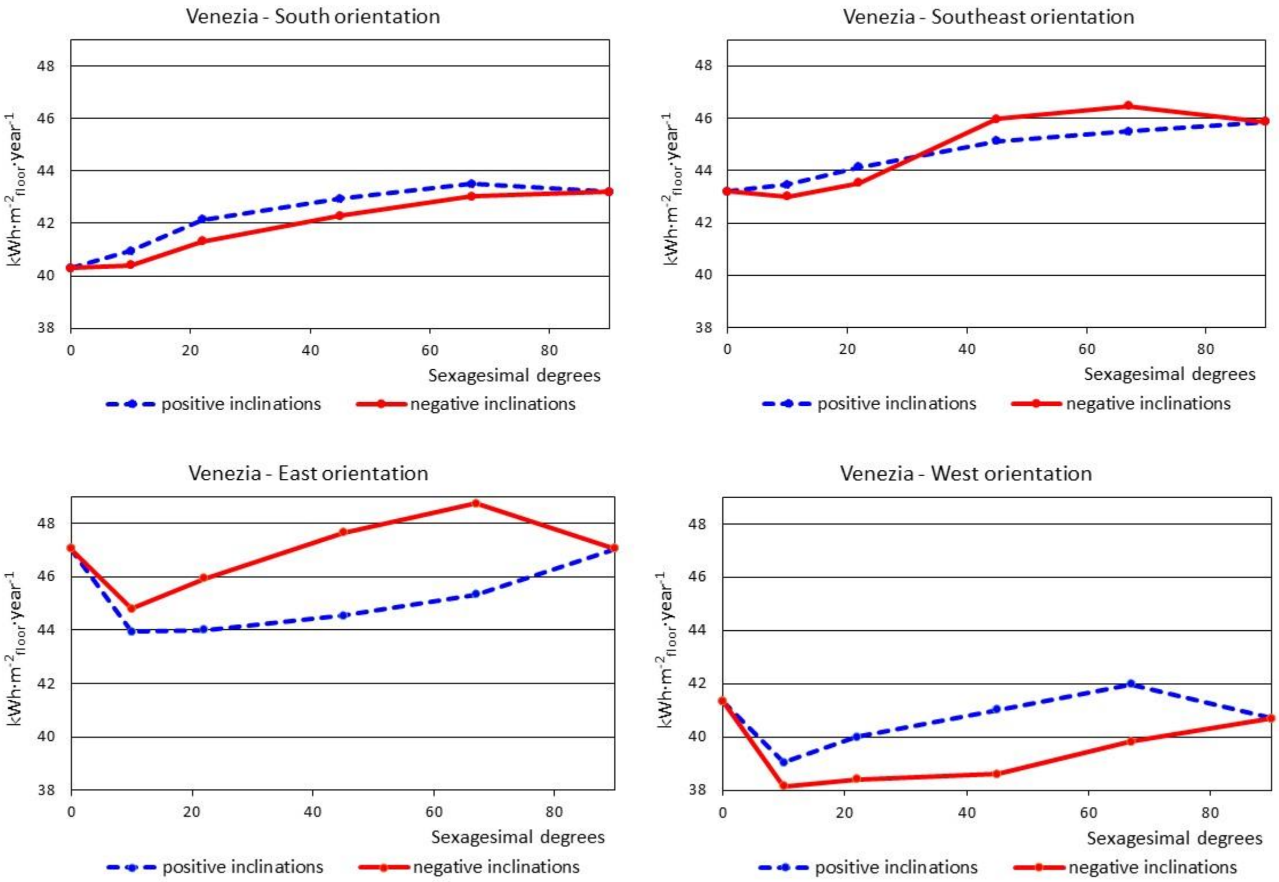

Figure 3: Array of fixed slats with minor axis orthogonal to the façade, total annual primary energy demand as a function of the lateral slope in the absence of glare control

By introducing solar control aimed at visual comfort through an internal curtain things change. Still examining fixed slats with the minor axis perpendicular to the facade, in general for all orientations examined the vertical arrangement of the slats major axis becomes the most convenient. This is due to the greater frequency of excessive values of the DGI that are found with the arrangements close to the horizontal one. Visual discomfort causes the curtain to be lowered, therefore a lower internal illuminance and greater energy consumption due to the lamps. The excessive values of the DGI are primarily due to the position occupied in the visual field by the upper part of the slats directly radiated by the Sun and not to the visible sky. This makes the lateral inclinations of the slats vertical or close to verticality more convenient with all the orientations of the façade (Figure 4). The differences in total energy demand between positive and negative inclinations are therefore due to a different number of cases of visual discomfort.

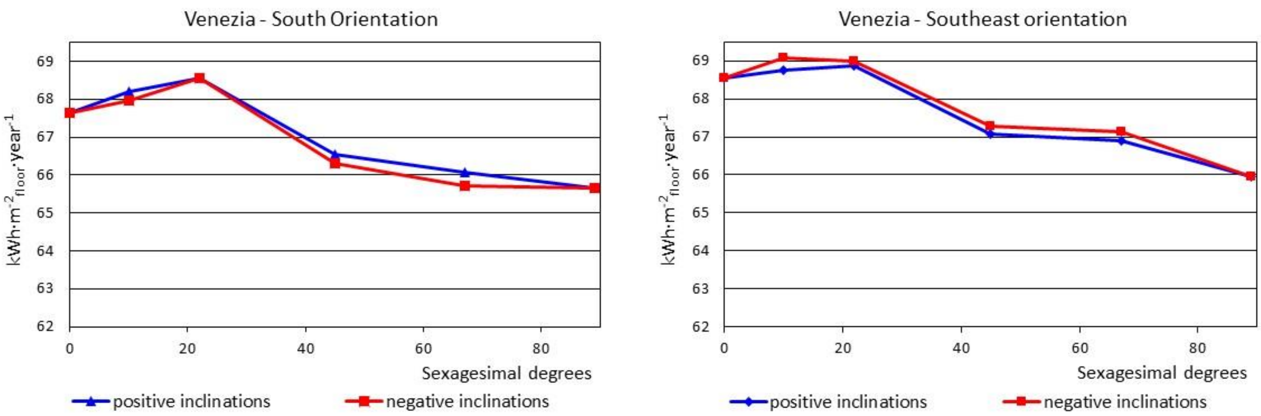

Figure 4 (a): Array of fixed slats with minor axis orthogonal to the façade, total annual primary energy demand as a function of the lateral slope in the presence of glare control operated by means of an internal blind

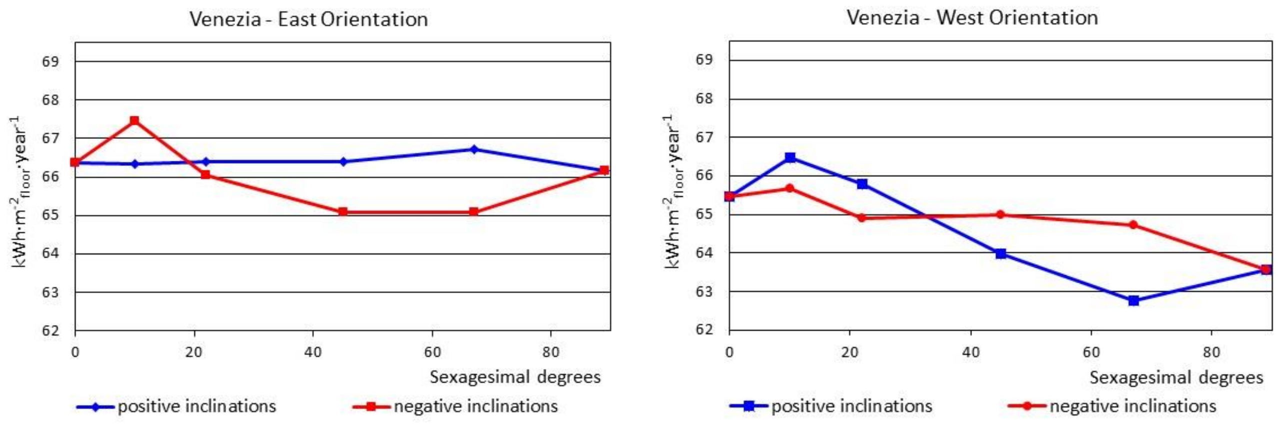

Figure 4 (b): Array of fixed slats with minor axis orthogonal to the façade, total annual primary energy demand as a function of the lateral slope in the presence of glare control operated by means of an internal blind

If the slats are fixed but with a downward inclination of their outermost edge of thirty degrees, the cases of glare due to the excessive luminance of their upper part are reduced, therefore, the differences between the various lateral inclinations are drastically reduced. Even more so if the slats are tilting in the direction perpendicular to the façade, the downward inclination of their outermost edge reduces the cases of glare due to the excessive luminance of their upper part in more cases, therefore there are significant energy savings compared to fixed slats. This is especially true when the slats longitudinal axis is horizontal. Therefore, the trend of energy demand as a function of the lateral slats inclination becomes that represented in the Figure 5. Variations in energy demand are almost exclusively due to artificial lighting. The advantages of the slats horizontal arrangement are greater with the south orientation of the glazed façade. The differences between the east and west orientations are always due to the effect of the time of use, which is longer in the afternoon.

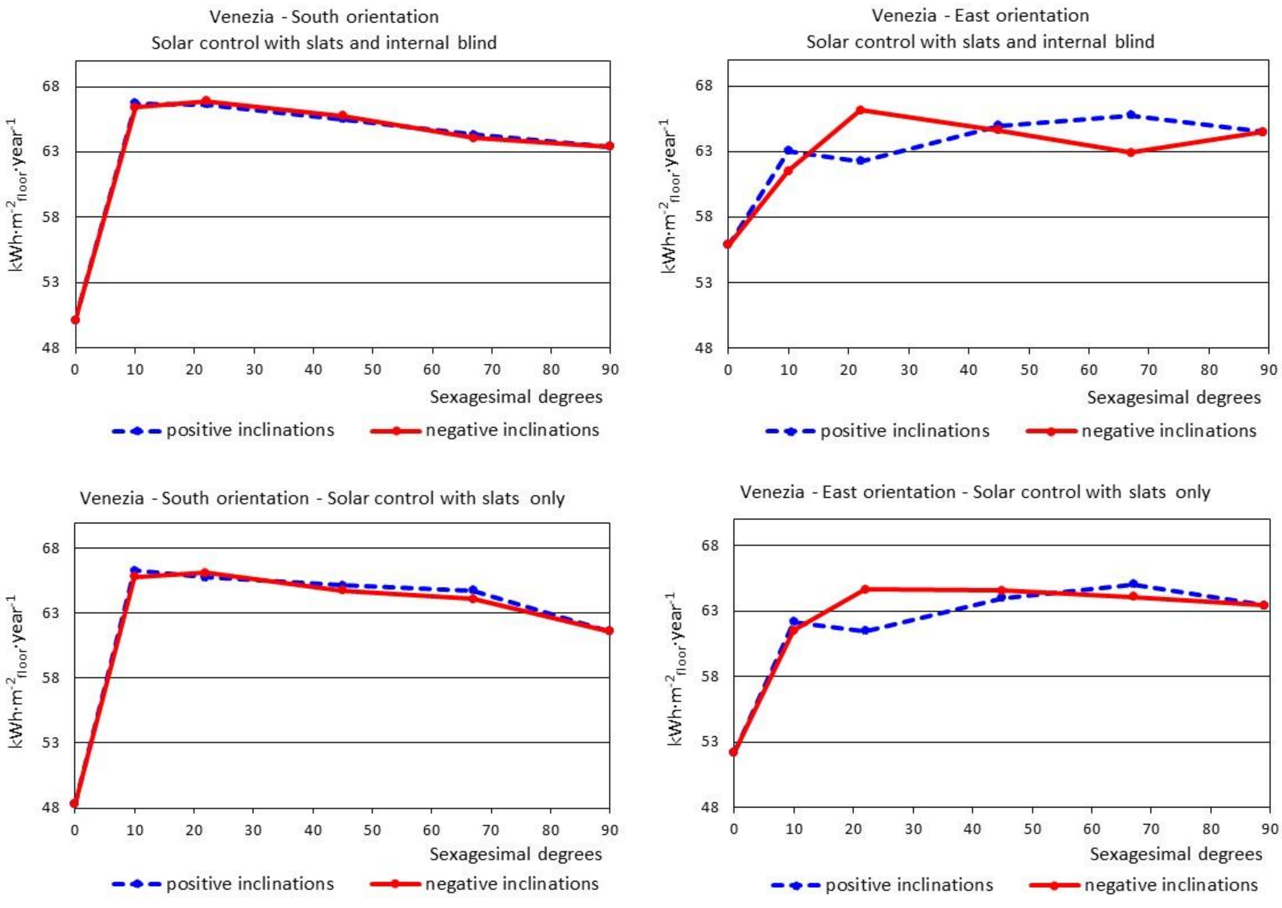

Figure 5: Array of movable slats, total annual primary energy demand as a function of the lateral slope in the presence of glare control operated by means of slats inclination and an internal blind (above) and by means of slats inclination alone (down).

In the case study, discomfort glare due to extensive light sources is the most frequent, it is evaluated by means of the DGI index (Figure 6).

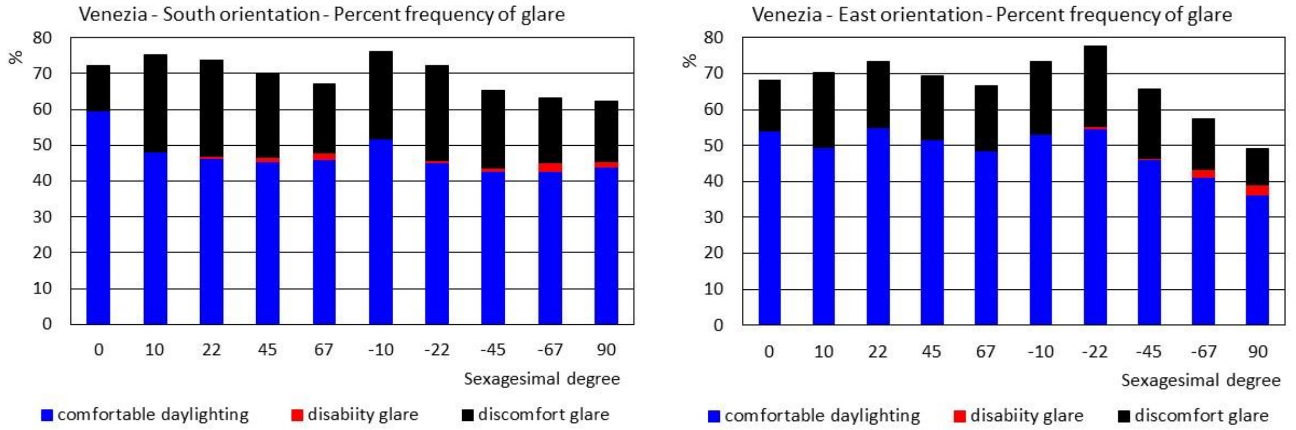

Figure 6: Solar control performed with movable slats, for each slats lateral slope percentage frequency of hours-occupant in visual comfort and discomfort conditions on the total hours-occupant, that are detected after the thermal load control actions, and before the glare control actions of various types, for south orientation (left) and east orientation (right) of the facade

The fact that the cases of discomfort detected do not always translate into increases in the energy demand from artificial lighting is because subsequent glare control actions do not always reduce the internal illuminance below the minimum value.

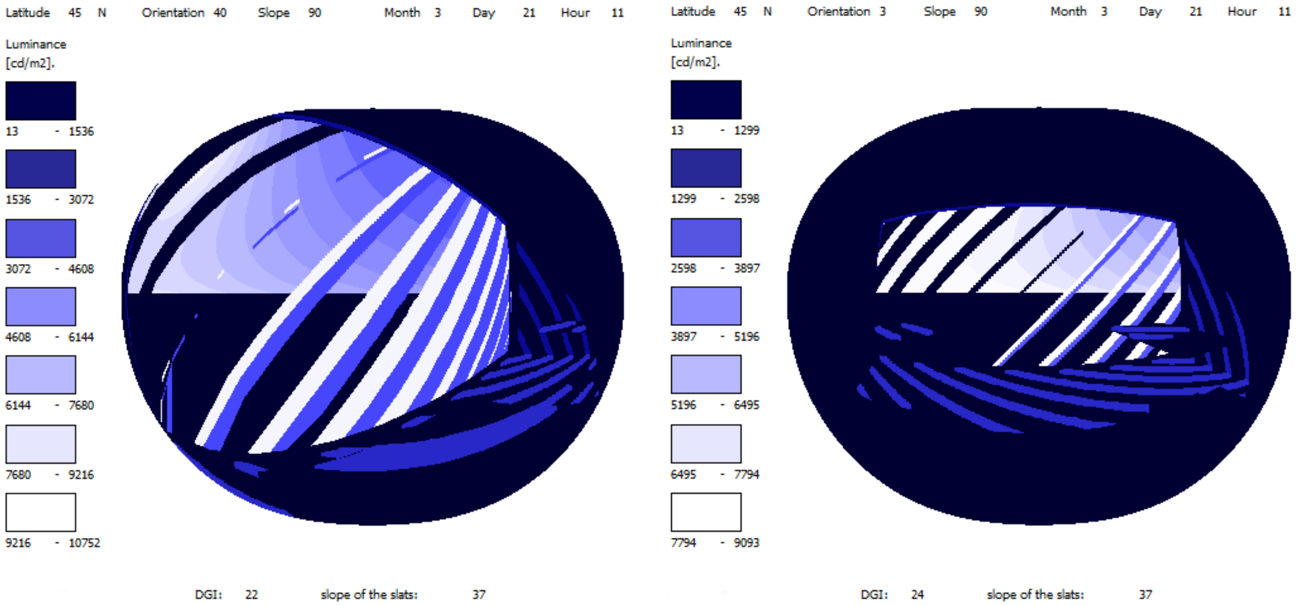

Figure 7: Examples of occupant visual field simulations, used by Ener_Lux software to calculate the DGI and UGR indices

The solar control strategy based on the use of slats alone is slightly more advantageous than the one that also involves the use of the internal curtain, particularly when the slats longitudinal axis is horizontal. This is because, with the same cases of visual discomfort detected, this strategy reduces less the incoming luminous flux (the transparency coefficient of the curtain is assumed to be equal to 0.5); therefore, it leads to less use of artificial lighting.

3.2. Slats equipped with PV cells

Two strategies for handling movable slats equipped with PV cells were compared: one is aimed only at maximizing photovoltaic electricity generation and the other is aimed at doing this while guaranteeing natural lighting in the room as much as possible. In both cases, to avoid glare, the internal curtain is used. Understandably, only positive inclinations of slats major axis were explored in the case of eastward orientations and only negative inclinations in the case of westward orientations.

The histograms shown in Figure 8 compare the various items of the energy balance of the room related to the first strategy and two orientations of the façade. The second strategy, which allows as much as possible natural lighting in the room, slightly penalizes PV production with east and west orientations, and penalizes it to a greater extent for the south orientation (Figure 9).

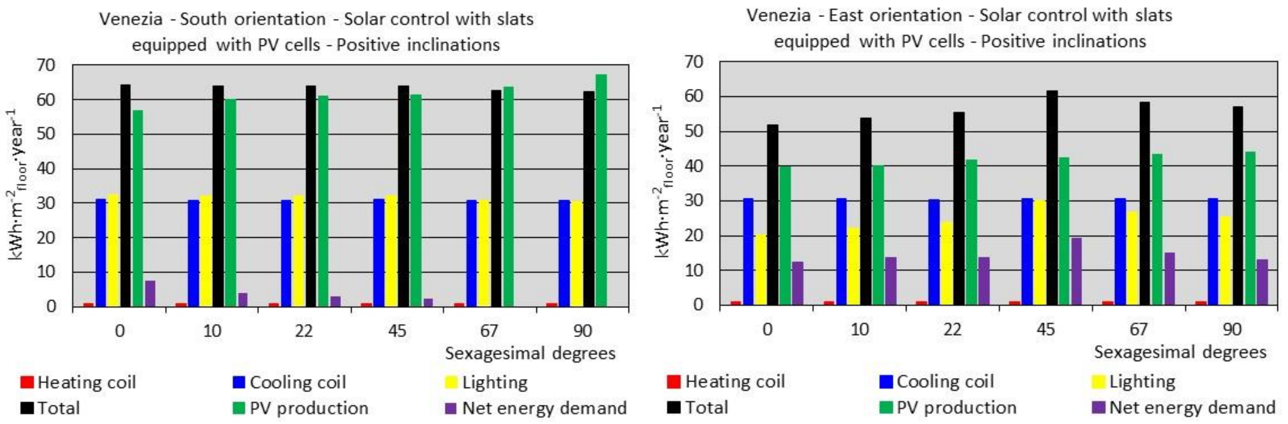

Figure 8: Examples of the values assumed by the annual primary energy demand for different uses and the production of photovoltaic electricity (always expressed in terms of primary energy) with the strategy aimed only to maximise the PV generation for two different orientations

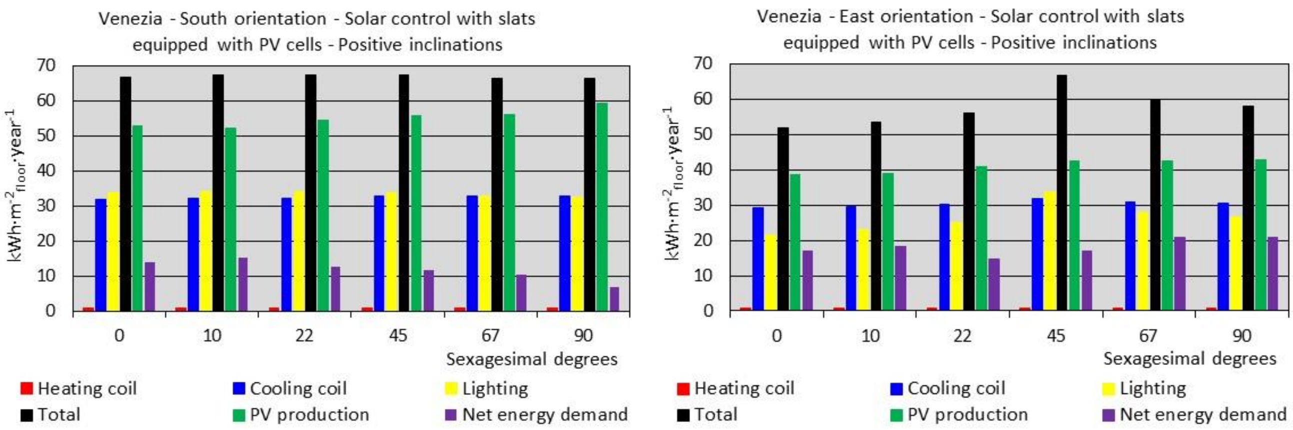

Figure 9: Examples of the values assumed by the annual primary energy demand for different uses and the production of photovoltaic electricity (always expressed in terms of primary energy) with the strategy aimed to guarantee the daylighting in the room as longer as possible for two different orientations

Of particular interest is the net primary energy demand, which is obtained by subtracting from the total room's energy demand the primary energy equivalent of photovoltaic electricity production (Figure 10). With both strategies, in the case of the east and west orientations of the façade it is not convenient to tilt the slats laterally, while in the case of the south orientation it is convenient a lateral slope as much as possible tending to verticality. Indeed, it allows to better exploit the solar radiation throughout the day, minimizing the angle of incidence of direct radiation on the slats.

Although PV production always tends to increase with the slats lateral slope, in the case of the east and west orientations the net demand does not always decrease as a result, because at the same time the energy demand for artificial lighting increases. The thing is more accentuated in the case of the west orientation, due to the time of use of the room that is more extended in the afternoon. With this orientation in fact the daylighting in the afternoon is often penalized by the use of the curtain to avoid the phenomena of glare.

The solar radiation data used are symmetrical with respect to noon, so, in the case of the first strategy and the southern orientation, the daily photovoltaic electricity generation of slats with the same lateral inclination, both positive and negative, is the same, but daylighting is required longer in the afternoon. Therefore, the slight differences that are found in the net energy demand are also due in this case to the energy demand for artificial lighting which is lower in the afternoon if the lateral inclinations of the slats are positive, with these inclinations in fact the upper face of the slats sees the brightest part of the sky and the incoming luminous flux is greater. For the same reason, the second strategy guarantees daylighting for longer with positive lateral inclinations, but this penalizes photovoltaic generation more, therefore the net primary energy demand is higher.

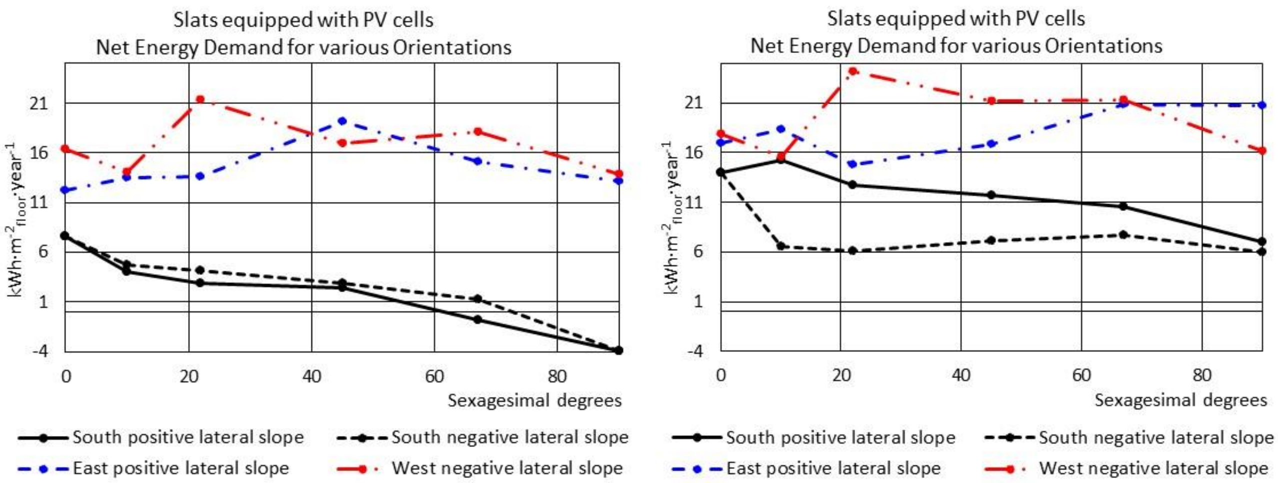

Figure 10: Net annual primary energy demand with slats equipped with PV cells. The diagram on the left is relative to a strategy aimed only to maximise the PV generation, the other to a strategy that seeks to guarantee the daylighting in the room as longer as possible

4. REFERENCES

Carbonari, A. (2017) 'Solar control of extensively glazed facades: a computer method for predicting the effects of various devices and building's thermal inertia', *SET 2017 – 16TH International Conference on Sustainable Energy Technologies. Bologna, 17-20 Luglio 2017*. Bologna: WSSET and Alma Mater Studiorum Università di Bologna.

Carbonari, A. (2023) 'Retrofit of Massive Buildings in Different Mediterranean Climates. Interactions Between Mass, Additional Insulations and Solar Control Strategies'. *Future Cities and Environment,* 9(1): 7, pp. 1–16.

Chauvel, P., Collins, J.B., Dogniaux, R., and J. Longmore (1982) 'Glare from Windows: current views of the problem', *Lighting Research & Technology*, 14(1), pp.31-46.

Commission Internationale de l'Eclairage - CIE (1995) *Discomfort Glare in interior lighting. Technical report 117*. Vienna: CIE.

Deutsches Institut für Normung - DIN (1979) *DIN 5035 Innenraumbeleuchtung mit künstlichem licht*. Deutsches Institut für Normung.

Ente Nazionale Italiano di Unificazione – UNI (1997) *UNI EN ISO 7730: Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. Milano: UNI.

Ente Nazionale Italiano di Unificazione – UNI (2000). *UNI/TS 10840: Luce e illuminazione Locali scolastici: criteri generali per l'illuminazione naturale e artificiale*. Milano: UNI.

Fanger, P.O. (1970) *Thermal Comfort*. New York: Mc Graw-Hill.

Hopkinson, R.G., Petherbridge, P. and Longmore, J. (1963) *Daylighting*. London: Heinemann

Robbins, C. L. (1986) *Daylighting, design and analysis*. New York: Van Nostrand Reinhold Company.

5. CONCLUSION

Simulations results show that for the case study, in the examined climate, the optimal arrangement of the slats major axis varies significantly depending on the solar control strategy adopted. In particular, the strategies based on the optimal inclination of the minor axis of movable slats, with or without the use of an internal curtain, turn out to be the most convenient and make the horizontal arrangement of the slats major axis more advantageous for any orientation of the façade, except in the case that the slats are equipped with photovoltaic cells. In this case, in fact, when the façade is oriented towards the east or west it is not convenient to tilt the slats laterally, while in the case of the southern orientation it is convenient a lateral slope vertical. Indeed, it allows to better exploit the solar radiation throughout the day, minimizing the angle of incidence of direct radiation on the slats.

The assumptions made regarding the intended use of the room and its construction technologies, mean that artificial lighting significantly influences the total energy demand. The period of use of the lamps is conditioned by glare control strategies, which can significantly reduce the internal illuminance. In this study it was assumed a spatially uniform artificial lighting system consisting of fluorescent lamps, but a more localized and less powerful lighting system would lead to lower overall energy demand and fewer differences between the various configurations of the slats.