Energy demand, Thermal and Luminous Comfort in Office Buildings: a computer method to evaluate different Solar Control Strategies

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ABSTRACT
Many contemporary office buildings are characterized by large glazed surfaces, often located without any consideration about orientation. Without a suitable solar control strategy, this fact implies several problems related to visual comfort, thermal comfort and energy demand, which is mainly related to HVAC and, to a smaller extent, to artificial lighting. Moreover, if the office room is large, the values of physical parameters influencing comfort are relevantly variable from point to point, mainly as a function of the distance from glazed surfaces. Typically, daylighting requirements of occupants located far from the windows can conflict with the thermal comfort requirements of occupants located next to the windows. In this work a case-study is analysed. It consists in a medium size office room located in a typical office building, in an urban context of the Northern Italy. Different solar control devices and related control logics are compared; their effects on global comfort conditions and energy demand are assessed. The considered devices consist of different kinds of movable external slats, some of which incorporating PV cells. This analysis is performed by means of a specific software: "Ener_Lux", already presented in previous PLEA Congresses. Once defined the kind of devices and the related operating logic, the program simulates the dynamic thermal and luminous behaviour of the physical system, provides various comfort assessment index values and calculates the primary energy demand for HVAC and lighting.

INTRODUCTION
Many Contemporary office buildings are characterized by large glazed surfaces. Without a suitable solar control strategy this peculiarity implies several problems, both with regard to visual and thermal comfort and with regard to energy demand. The latter is mainly related, in Mediterranean climates, to HVAC and to a smaller extent to artificial lighting. Moreover, if the office room is large, the values of physical parameters influencing comfort vary relevantly from point to point; this variability is mainly due to the distance of the occupant from glazed surface. Consequently, for instance, lighting comfort requirements of occupants located far from the windows can conflict with the thermal comfort requirements of occupants located closer to the windows, requiring a reduction of entering solar radiation, because of overheating and glare.

These problems are particularly relevant in office buildings realised in Italy in the last decades, characterised by extended glazed surfaces, located in any façade with no care about orientation. In this
work a case-study is analysed. It consists in an office room of medium size located in a typical office building, in an urban context of the Northern Italy. Different solar control devices and related control logics are compared, focusing on their effects on global comfort conditions and energy demand.

In particular, the considered devices are listed below.

1. Different kinds of external adjustable slat systems, with mirror-like or diffusing surfaces.
2. A double skin façade incorporating an adjustable slat system split into two parts: the upper part is composed by slats having mirror-like reflecting upper surfaces, whereas the lower part is composed by packable slats with diffusing surfaces.
3. Two kinds of adjustable external slat systems incorporating PV cells.

All of these devices are combined with an internal diffusing screen, aimed to avoid glare then the slats tilt allows the entry of direct radiation. As a general rule, the control logics are aimed to minimize energy demand and to allow daylighting for the maximum span. All of the analyses presented in this paper are based on computer simulations performed by means of software Ener_Lux, previously presented in PLEA Congresses, in particular at PLEA 2012 (Carbonari, 2012).

**THE SOFTWARE**

Software Ener_Lux is mainly aimed at the study of solar control devices and related control strategies. Therefore it takes into consideration the physical system composed by a room, its glazed surfaces, internal and external solar control devices (slats, blinds, overhangs and any element shading the opening) as well as the surrounding urban environment, including the building containing the room under investigation.

Once defined the kind of devices and its control logic, the program simulates the dynamic thermal and luminous behaviour of the physical system at hourly time-steps, and provides: Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) (Fanger, 1970) and Daylighting Glare Index (DGI) values, Hopkinson et al. (1963), together with other controls about the visual environment quality. Then it calculates the energy demand for HVAC and artificial lighting.

![Figure 1](image) Scheme of the Ener_Lux calculation flow. The figure shows the behaviour of the program when referring to a double slat array, one of which is provided with mirror-like upper surfaces.
When adjustable devices are simulated, all the solar control actions aimed to maintain thermal and luminous comfort, such as slats tilting or screen lowering, are automatically simulated: in such cases, the program modifies the system geometry configuration and repeats the simulation of the hourly time-step. The check against visual discomfort conditions is performed only when the lamps are turned off, as shown in Figure 1.

The indexes used for the assessment of the visual comfort are calculated by means of an algorithm simulating occupants’ visual field, as shown in Figure 2. Different kinds of glare are considered: veiling glare due to direct radiation impinging on the visual task, that can imply thermal discomfort too, big differences of luminance values between different points in the visual field, and glare due to large luminous sources (typically the sky seen through the windows), evaluated by DGI calculation. When one of these kinds of discomfort issues is detected, the program simulates a solar control action.

In case of thermal discomfort, averaged in the room as a whole, the indoor air set-point temperature may be modified to reach the true value of PMV (that has to be between -0.5 and 0.5 according to the standard ISO 7730) and the hourly time-step calculation is repeated. However, in this work this feedback is not performed.

Figure 2 Simulation of an occupant’s visual field at the same time on different illustrative days, in presence of double slat arrays. The slats of the upper array are mirror-like reflecting.

THE CASE STUDY

The case-study consists in an office room of medium size: 5.88 m wide along the façade, 6.18 m deep orthogonally to the façade, and with internal height equal to 3.27 m. The room is located in an office building of the industrial district of Venice (Marghera). The building presents an entirely glazed façade almost south oriented (with 22° West azimuth). In the local climate this orientation is the less favourable during the cooling period. Actually, this façade is equipped with a system of tiltable slats incorporating PV cells, as shown in Figure 3 (b). At this side of the building a room at the second floor was chosen, to take into account the shading effects due to surrounding buildings. However, considering the distances from these buildings, there are not remarkable differences in solar irradiation between the second and the top floor. For comparison, a top floor room too has been simulated: when equipped with diffusing slats (see later) its total annual primary energy demand is 4.4% lower than in the case study.

The building structure is composed by reinforced concrete. Internal walls are in hollow bricks 0.08 m thick, with 0.02 m thick plaster layer on both the sides. Floors are built in hollow bricks and reinforced concrete: 0.24 m is the construction thickness, plus 0.06 m of screed and flooring and 0.02 m of plaster in the lower part. The only external surface of the room is the glazed one, composed by a double glazing of 0.006 m glass layers, and a 0.012 m air gap (overall U value: 2 W·m⁻²·K⁻¹). All the other internal enclosing surfaces are considered as adiabatic.
Four occupants are located in the room, at different distances from the glazed surface. To assess the visual comfort level for each position the worst line of sight has been considered: i.e. the one implying the higher contrast in luminances within the visual field. Thus, the glazed surface has to be present in it but it is empirically assumed that it cannot occupy more than half the visual field; otherwise the occupant’s eyes adapt themselves to the luminance of the external landscape.

Internal gains consist of: sensible and latent thermal flow from occupants (4 people - 65 W of sensible thermal power and 65 W latent), office devices (4 computers and 1 printer for a time average total power equal to 300 W) and fluorescent lamps (luminous efficacy: 91 lm/W, total power: 732 W).

To calculate the primary energy demand related to heating, ventilation and air conditioning (HVAC), it is assumed that the room is equipped with a full air centralized loop, and the daily time of utilization is from 09:00 (but the plant is activated one hour before) to 19:00. Although it is not the best efficient solution, it is assumed that the warm fluid is provided by a gas-boiler and the cold fluid by an electrically driven chiller (vapour compression chiller). Internal set-point temperatures are assumed to be 20 °C in winter and 26°C in summer (as prescribed by the Italian law), whereas in the middle season it is assumed equal to the daily average external temperature, because the clothing of the occupants is adapted to it. The relative humidity setpoint is assumed equal to 50% all over the year.

**Figure 3**  (a) The office building in its urban context, image from Google Earth (b) the actual configuration of the building (courtesy of Zintek Srl).

**Figure 4**  (a) Geometrical model of the physical system, the figure shows the position of the examined room inside the building (b) examined room model with workplaces.

**THE EXAMINED SOLAR CONTROL DEVICES AND THEIR CONTROL LOGICS**

The following solar control devices and related control logics are analysed and compared with reference to this office room.

**External adjustable diffusing slat system.** The vertical distance between slats (0.5 m) is equal to their depth (normal to the façade when the slat is horizontal). Slats surfaces are diffusing and their total
reflection coefficient is equal to 0.6 for both the sides, whereas mirror-like reflection coefficient is assumed equal to zero. All the reflection coefficients used in this paper pertain to the total solar spectrum as well as the visible range. Slats are controlled by a seasonal logic: in each moment, slats are inclined at an angle that allows the entering of the only solar energy fraction that can contribute to cover the sensible thermal load, and avoiding overheating. Anyway, the entering solar radiation cannot be lower than the one required for daylighting, ensuring a minimum illuminance value (500 lx according to Italian standard UNI 10380) in the most critical workplace.

**Double array of external slats.** This system consists of two slat arrays. The upper slat array starts at 1.7 m from the floor and its slats have a mirror-like reflecting upper side (total reflection coefficient: 0.9, specular reflection coefficient: 0.9), whereas the lower side is absorbing (total reflection coefficient: 0.1, specular reflection coefficient: 0.0), to prevent downward reflected beams from entering the room. These slats are controlled in order to redirect the solar beams upwards inside the room, avoiding direct radiation on occupants and visual tasks. To avoid the entry of direct radiation in winter, the vertical distance between slats is reduced to 66% of their depth (i.e. 0.5 m \* 0.66 = 0.33 m). The lower array is equal to the diffusing array described above. Also in this case the control logic is seasonal, but a little more complex. As a first step, the tilt of the upper array is adjusted so that the larger part of the incoming radiation is redirected upwards, whereas the tilt of the lower array is adjusted to allow the solar radiation to enter the room in the amount needed for heating purpose. When the lower array is completely closed and the entering radiation exceeds the required value, the upper array is adjusted to reduce it as well. This adjustment stops when the incoming radiation reaches the minimum value necessary for daylighting.

**Double skin façade.** In this case one laminated external glass (0.01 m thick) is present at 0.9 m from the previously described glazing. In the 0.9 m void a double slat array take place, close to the external glass. It is similar to the one described above, but in this case the slats, protected by the external glass, can be smaller and less robust. In particular, the lower array of diffusing slats can by packable to allow the entry of a higher solar power when required. The slat control logic is the same as for the double array system described above. During the cooling period the void is ventilated and it is assumed at the same temperature as the outdoor air, whereas in the heating period the minimum ventilation necessary to avoid condensation problems is provided, and the temperature of the air in the void assumes an intermediate value between the indoor and outdoor air temperatures.

**External slats incorporating PV cells.** Two different types of slats incorporating PV cells were studied. In the first configuration (type A), the vertical distance between slats (0.5 m) is equal to their depth, but the PV cells occupy only 66% of the slat upper surface (and at the outdoor side), because in this configuration the remaining part is shaded for the most of the time. The reflection coefficient value is assumed equal to 0.2 for PV cells and 0.8 for the remaining slat upper and lower surfaces; therefore the average value is 0.39 for the upper surface. In the other configuration (type B) the vertical distance between slats is the same but the depth is reduced by 33%. This way a fraction of the direct solar radiation too enters the room during some winter periods and lowers the need for artificial lighting.
Moreover, the PV cells are less shaded, in particular as regards sky diffuse radiation, and their electrical production is higher. In both cases (A and B), initially, the control logic was finalized to maximize only the electrical production of the PV cells; therefore, the angle of incidence of solar beams on slat surfaces (the angle between the solar beam and the normal to the slat surfaces) was always minimized. Then, for type B, this logic was modified in order to allow the radiation needed for daylighting to enter the room, when available. This modification lowers relevantly the total primary energy demand, since the reduction in electrical production (limited to some hours of winter days) is negligible when compared with the achieved reduction in energy demand for lighting and consequently for cooling.

In all of the solar control systems described above, when the entering solar direct radiation can cause glare, an internal diffusing blind is lowered; it consist of a dark (grey 80%) metallic foil micro-pierced for 50% of its surface. Its light transmittance is equal to 50%, but it reduces the solar heat gain by 10% approximately. As a matter of fact, the energy absorbed by the foil is re-emitted as infra-red (IR) radiation, that cannot transfer through the glasses, and only the half part, approximately, of the short-wave radiation reflected from the foil can do it. This blind is used only in the heating period, since in the rest of the year the slats block the solar beam radiation.

ANALYSIS OF THE RESULTS

The solar control devices are compared under two points of view: room total primary energy demand and global comfort conditions. Therefore, the thermal flows provided to the room by the plant, are converted into primary energy as a function of current values of boiler efficiency, chiller coefficient of performance (COP), and global system efficiency. The electric energy absorbed by the HVAC system as well as by lighting system is converted into primary energy by means of the related Italian electric system conversion efficiency (equal to 36%). The electric energy generated by PV cells is converted into equivalent primary energy using the same conversion coefficient and is subtracted from the total primary energy demand. For this reason, in some periods, the total annual primary energy demand appears as negative as shown in Figure 7 (b).

Energy performance. The room under investigation is characterized by relevant internal gains and more than the half part of these comes from lighting system (732 W), when turned on. For this reason the cooling loads, present in winter too, are dominant in the composition of primary energy demand. In facts, with the exception of the first one/two hours at some winter mornings, when lamps are turned on cooling loads usually take place in winter too. For this reason, the level of daylighting achieved inside the room is decisive to define the suitability of a solar control system. Probably this situation can change adopting different lighting system, mainly consisting in task lighting by means of individual lamps located at each workplace (the related power can be reduced from 732 to 320 W), but the simulated lighting system is actually far more diffuse in Italian office buildings.
Among the devices without PV cells, the diffusing slats are the most energy efficient solution. The external double array with specular slats is less convenient, because of the lower total incoming radiation during the winter, consequently the artificial light is used for longer time and cooling loads are higher. The double skin system is fairly less convenient than the last one: the lower thermal losses reduce the energy demand for heating, but this benefit is overcome by the increase of energy demand for lighting and cooling.

The annual electrical production of the devices incorporating PV cells is in the same order of magnitude as the room total energy demand, thus they are more convenient than other solar control devices. The first kind of device (type A) is controlled only to maximize the electricity generation, consequently the entering solar direct radiation is always blocked by slats and the entering solar diffuse radiation is reduced too. Therefore artificial light is turned on for longer time and, for short periods, useful solar gains are minimized, whereas the consequent increase in energy demand for lighting and HVAC corresponds to a small fraction (29%) of the primary energy equivalent to electricity generation.

Anyway, the best energy effective system is the one with less deep slats (type B), which allows a larger amount of solar radiation to enter the room, in particular when it is controlled in order to minimize the use of artificial lighting. In this case, in some months the room energy balance is positive: the primary energy equivalent to the PV electricity generation is higher than the room energy needs.

**Figure 7**  
(a) monthly primary energy demand (per square meter of floor area) related to HVAC and lighting systems for various devices (b) total monthly primary energy demand, including PV generated electricity (with negative sign) [kWh/(m² floor month)].

The luminous comfort. A first comparison can be done on the basis of the total number of hours in which the DGI value is out of limits for at least one occupant and the internal blind is lowered. The limit value for DGI is assumed equal to 21 according to Italian standard (UNI 10840). Following this criteria,
the external double array with mirror-like slats appears as the most comfortable configuration (the blind is used only in the 4% of the time) followed by the other two devices without PV cells, whereas all the devices incorporating PV present a worse behavior (the blind is used in the 37-57% of the time). In effect The DGI value exceeds the limit when the more luminous part of the sky is extensively visible, or when the internal average luminance is very low and the contrast with the visible sky is high, as it occurs in case of slats incorporating PV cells, particularly in type A, that assume every time the tilt necessary to block solar direct radiation. Another kind of discomfort can be caused by the solar beam radiation impinging on visual tasks; this is more frequent (during the winter) in case of double slats arrays.

At last, the two devices equipped with specular surfaces provide the higher uniformity of internal illuminance.

**Thermal comfort.** Using the internal air temperature as the indoor environment control parameter, the differences in the thermal comfort are mainly influenced by internal surface temperatures. Comparing different devices: comfort conditions are generally better with devices not provided with PV cells and controlled by a seasonal logic, as shown in Figure 8 (a). In these cases the temperatures of internal glazing surface and internal surfaces exposed to the incoming radiation are higher during the cold season and lower during the warm season. The devices incorporating PV cells intercept direct radiation for almost all the time, but in the cooling season the entering radiation reflected by the slats is higher than in the other cases. Consequently, the internal temperatures are lower during the cold season and higher in the warm season. The spatial uniformity of PMV values is generally high (the differences are lower than 17% in winter and 2% in summer); particularly in the case of double skin (the differences are lower than 11% in the colder month too). This is due to the glazing internal surface temperature that is closer to the internal air temperature.

**CONCLUSION**

Overall, the less deep slat system incorporating PV cells (type B) is the most energy efficient device, particularly when controlled in order to allow the solar radiation necessary for daylighting to enter the room whenever available. In this last case, the PV electric generation is slightly reduced during some winter periods, but the problems connected to artificial lighting (such as lamps energy demand and cooling load) are appreciably reduced. Moreover in the room considered, characterized by relevant internal heat gains, the reduction of useful solar gains concerns only some short winter periods.

However all the systems provided by PV cells present worse performance regarding visual and thermal comfort. To avoid this problem it is possible to forecast some possible device evolutions with the purpose of combining the best energy and comfort performances, such as the following ones.

1. An array of mirror-like reflecting slats able to change the vertical distance between the elements, depending on the Sun position, thus entering solar radiation will be reduced only as a function of slats reflecting coefficient, but this kind of device is currently not available.
2. A double slat array with mirror-like reflecting slats in the upper part and slats incorporating PV cells in the lower part, controlled by the logic of type B.

**NOMENCLATURE**

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<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>PMV</td>
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<tr>
<td>DGI</td>
<td>Daylighting Glare Index (DGI) values, Hopkinson et al. (1963).</td>
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**REFERENCES**

