Urban Covered Courtyards in Mediterranean Climates

A method for optimizing environmental control strategy

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Abstract: Covering urban courtyards allows you to create interesting public or semi-public spaces, sheltered from bad weather and possibly with a controlled climate. In addition, the use of a transparent or semi-transparent roof allows you to take advantage of natural lighting.

The use of this type of roof is a common solution in the countries of central and northern Europe, but difficult to apply in Mediterranean temperate climates, because it would cause overheating for a good part of the year. This unless appropriate solar control strategies.

In this work, a case study was taken into consideration. It is the courtyard of a former Venetian convent. With reference to it, some types of partially transparent roofing and some solar control strategies were compared by means of computer simulations. The various solutions were compared from the point of view of visual and thermal comfort, as well as from that of primary energy demand for supplementary artificial lighting and possible energy demand for heating, ventilation and air conditioning if the relative system is present.

Given the diffusion of this type of courtyards in the Italian territory, its thermal and luminous behavior has also been simulated in the warmer climate of Palermo.

Simulation's results show that the better solutions are those based on the use of dynamic solar control devices.

Keywords: covered courtyard, solar control, comfort

1. INTRODUCTION

Covering urban courtyards make it possible to create interesting public or semi-public spaces, sheltered from bad weather and possibly with a controlled climate. In cities like Venice, when the climate allows it, urban spaces are often used for social activities such as outdoor film screenings, neighborhood parties, meetings, outdoor bars.

In addition, the use of transparent or semi-transparent roof allows you to take advantage of natural lighting (Berardi et al., 2014; Rymarov, 2019; Taleghani et al., 2014). This is a common solution in the countries of central and northern Europe; but it is difficult to apply in temperate Mediterranean climates. Indeed, it would cause overheating for a large part of the year, if appropriate design choices are not taken in order to control the solar radiation entering through the roof (Aldawoud, 2013; Aram & Alibaba, 2019; Palma, 2014; Salata et al., 2016; Wang et al., 2014; Yaşa & Ok, 2014). In fact, these climates are often characterized by cold winter and hot-humid summer, with a high seasonal variability of the benefits from incoming solar radiation, therefore of the optimal transparent part of the roof. Its oversizing could result in high thermal losses in winter and overheating in the rest of the year, while its undersizing would penalize daylighting levels especially in winter. Therefore, it is advisable to explore the possibility of using variable geometries of the transparent area by means of appropriate solar control devices, e.g. curtains, movable slats or more complex daylighting systems.

In this work, a case study was taken into consideration; it consists of the courtyard of the former Venetian convent of San Pietro di Castello (Figure 1). Currently the buildings surrounding the courtyard are used as dwellings. With reference to it, the inclusion of a partially transparent roof has been hypothesized (Figure 2 and 3) and various solar control strategies were compared.

Figure 1: The examined courtyard

The study was performed only by means of unsteady state building energy simulations. The software operated on a simplified digital model of the courtyard. In formulating the solar control strategies, the criterion of optimizing the conditions of thermal and luminous comfort has been adopted, guaranteeing daylighting as much as possible. Given the diffusion of this type of courtyard in the Italian territory, its thermal and luminous behavior has also been simulated in the warmer climate of Palermo.

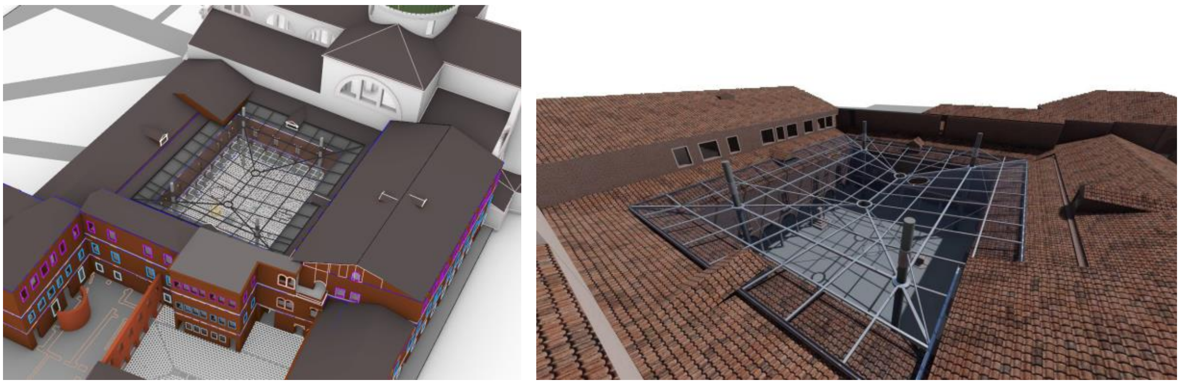

Figure 2: Schematic representation of the hypothesized roof

Figure 3: Section of the courtyard with the hypothesized roof

2. THE CASE STUDY

The digital model of the court is simplified from the geometric and thermo-physical point of view; it includes the roof, the walls of the buildings delimiting the courtyard and the ground of the same.

These are buildings of the sixteenth century with structural internal and external brick walls, 0.35 m thick, plastered on both sides: their total thickness is about 0.4 m, their transmittance (U-value) is about 1.65 $W \cdot m^{-2} \cdot K^{-1}$, and their front thermal capacity (C_{front}) is about: 640 $kJ \cdot m^{-2} \cdot K^{-1}$. Windows occupy approximately 10% of the façade surface, a double-glazing with wooden frame was assumed, with U-value equal to 1.69 $W \cdot m^{-2} \cdot K^{-1}$. It has been assumed that the interiors of these buildings are maintained in every season at the comfort temperatures by means of their systems.

The courtyard is paved with stones, about 0.15 m thick. In the thermo-physical model used for the simulations a 0.5 m thick layer of soil was included. The total frontal thermal capacity of this floor was estimated equal to 3704 $kJ \cdot m^{-2} \cdot K^{-1}$ and its U-value is about 1.65 $W \cdot m^{-2} \cdot K^{-1}$.

In a first phase, only a partial confinement of the covered urban space and the absence of any mechanized heating, ventilation and air conditioning system (HVAC) were hypothesized. Therefore, the various solutions were compared only from the point of view of visual and thermal comfort, as well as from that of primary energy demand for supplementary artificial lighting. It is assumed that the lamps are switched on when the natural illuminance is less than 300 lx. Subsequently, the hypothesis of totally confining the courtyard and inserting a full air modular HVAC system was considered. This system is sized for the maximum presence of 100 people. In this case, design solutions were also compared from the point of view of primary energy demand of this system.

The following types of roof and solar control strategies were compared:

- a translucent roof in PVC, 0.008 m thick with U-value equal to 4.64 $W \cdot m^{-2} \cdot K^{-1}$ (e.g. courtyards of British Museum in London or M9 Museum in Venezia-Mestre),
- a double-glazed roof, with U-value equal to 1.6 $W \cdot m^{-2} \cdot K^{-1}$, and a semi-transparent and diffusing internal fabric curtain. Its coefficient of transparency is 0.5, while the internal and external reflection coefficient is 0.425 both in energy and light field. The curtain is mobile and is used when necessary to avoid glare phenomena (e.g. courtyards of the California Institute of Sciences in San Francisco or Sony Center in Berlin),
- the same roof in transparent glasses of the previous point with external mobile slats system (Figure 4). Slats are controlled in order to minimize energy demand for internal environmental control, if HVAC plant is present, and optimize general comfort conditions (e.g. foyer of Muse Museum in Trento),
- the same system described in the previous point combined with the semi-transparent and diffusing internal curtain described above. In this case, the external slats are inclined in order to minimize energy demand and optimize thermal comfort, while the internal curtains are positioned when necessary to avoid any glare phenomena if they are detected,
- An opaque roof with four light tubes served by heliostats (e.g. foyer of the Airport of Manchester). In this case the opaque roof is made up of 0.15 m thick sandwich panels, with external and internal steel cladding and inner expanded polystyrene insulation material, U-values: 0.6 $W \cdot m^{-2} \cdot K^{-1}$. The heliostats are of the type shown in Figure 5 and are stably combined with a fixed internal diffusing element. The

section of the light tubes occupies 6.33% of the roof area, the U-value of the device is equal to 0.35 $W \cdot m^{-2} \cdot K^{-1}$. The values shown in the Table 1 are averaged on the surface.

The possibility of inserting PV cells on the mobile slats, occupying 80% of their surface, or on the 60% of the roof equipped with heliostats was also explored.

The main thermophysical characteristics of building elements are summarised in Table 1.

Table 1: Main thermal characteristics of the classrooms

Configuration	U-value [$W \cdot m^{-2} \cdot K^{-1}$]	C_{front} [$kJ \cdot m^{-2} \cdot K^{-1}$]
Brick wall 0.40 m thick	1.65	640
Windows	1.69	37.3
Ground of the courtyard	0.55	3704
Roof in PVC	4.64	14.8
Double-glazed roof	1.64	40.8
Opaque roof with four light tubes	0.59	31.7

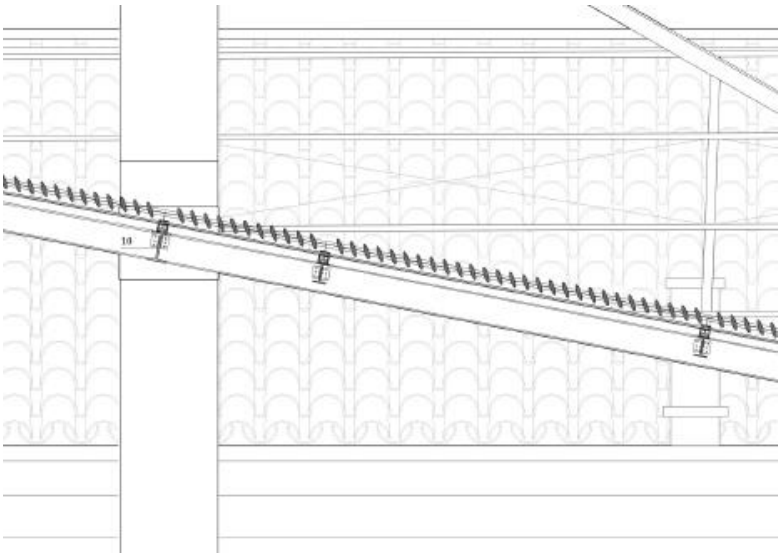

Figure 4: Section of the roof in glasses with external mobile slats

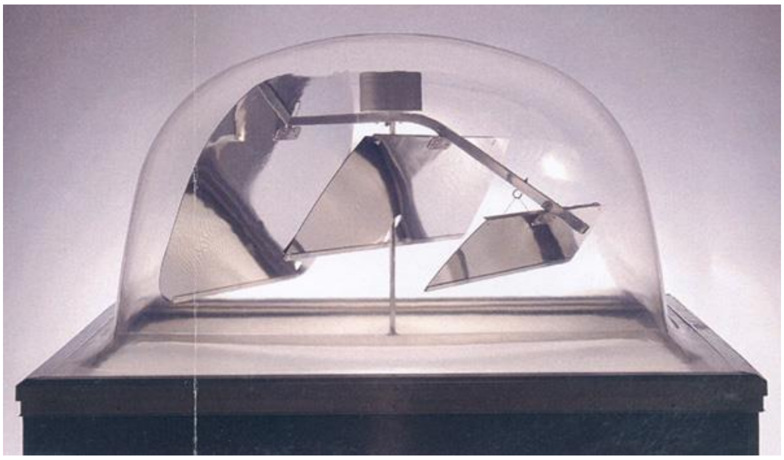

Figure 5: Sample of heliostat, system "Lux tracker". From catalogue of Lux Service Lucernari s.r.l. http://www.luxservice.it/

In the HVAC system, the heating and cooling coils capacities are sized with respect to the maximum summer and winter loads of the various locations examined, this is variable depending on the hypothesized solar control devices. In the most demanding configuration, which is the one with the roof in PVC, the heating coil design capacity is 53.8 kW in Venice and 34.8 kW in Palermo, while the cooling coil design capacity is -74.9 kW in Venice and -97.9 kW in Palermo. The corresponding maximum air flow rates are 5.35 $m^{-3} \cdot s^{-1}$ in Venice and 6.99 $m^{-3} \cdot s^{-1}$ in Palermo. Correspondingly, these capacities and air flow rates are greatly reduced when using the most performing roofs.

The air handling unit of the HVAC system is equipped with electrically driven chillers providing the cooling coils with cool water, while hot water for the heating coils is primarily provided by the condensers of the chillers, integrated by gas-boilers when necessary. The chillers have a nominal Coefficient of Performance (COP) equal to 4.5, which is modified according with the part load ratio, while boilers have an efficiency of 0.9. The primary energy conversion coefficient are 1.05 and 2.77 for gas and electricity respectively, in accordance with Italian standards.

3. METHODS

Normally this type of analysis is carried out using different software to simulate the thermal and luminous behaviour of the building, usually: *EnergyPlus* for energy and *Radiance* for lighting simulations. This does not allow simulating within each calculation step the interactions between solar control actions and energy demand for lamps and HVAC. Therefore, a specific homemade software, *Ener_Lux*, has been used here (Carbonari, 2012, 2017). It is mainly aimed at supporting the design of solar control devices and related control strategies. 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. It simulates the dynamic thermal and luminous behaviour of the physical system at hourly time steps.

Within each calculation step, it checks the conditions of thermal and luminous comfort relatively to some significant position of occupants inside the room by calculating the relative evaluation indexes. These positions must be chosen in the instruction phase of the program. Concerning the thermal comfort, these indexes are the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) (Fanger, 1970; UNI, 1997). In luminous field the calculated indexes are: Daylighting Glare Index (DGI) in case of wide light sources (Chauvel et al., 1982; UNI, 2000) or Unified Glare Rating (UGR) in case of smaller sources (CIE, 1995; Hamedania et al., 2019), and uniformity factor of the internal illuminances value (U_o) (DIN, 1979). The visual comfort check is performed only when the lamps are turned off.

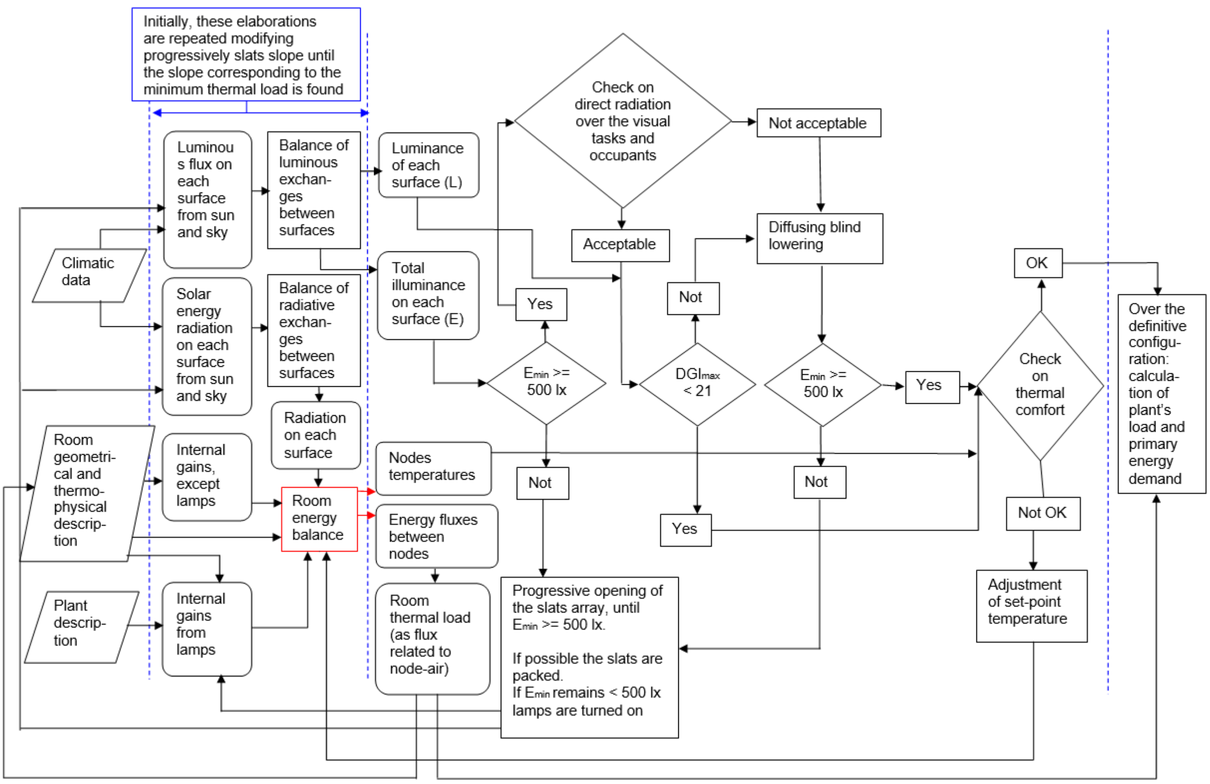

Figure 6: Flowchart of the software used, when simulating a solar control system including external slats and internal curtain

The position of the occupants in the room affects the calculation of the view factors between their bodies and the surrounding surfaces, therefore the mean radiant temperature (MRT) perceived by each occupant. The evaluation indices of luminous comfort are related to the position and possible lines of sight of each occupant, which must be specified.

Once the comfort checks have been carried out, any necessary feedback on the solar control devices and/or on the set-point temperatures, if a HVAC system is present, is automatically simulated and the calculation of the hourly time-step is repeated. When adjustable devices are present, all the solar control actions, such as slats tilting or screen lowering, are simulated by modifying the digital model. Then the program calculates the primary energy demand for HVAC and artificial lighting (Figure 6).

In energy field, the program uses an algorithm based on a finite difference method and heat balance of elementary zones (e.g. a single layer of a wall or a glass): a thermal grid model (Buonomano et al, 2016; Fraisse et al., 2002; Kämpf, 2007; Underwood, 2014;). This algorithm provides the thermal flows between the nodes and their temperatures. The temperatures of the nodes corresponding to the internal surfaces are also used for the calculation of thermal comfort indices. At present only one node, in the centre of the room, represent the air mass. To use more air nodes it would be necessary to sophisticate the model with a fluid-dynamic part, which is currently absent.

Starting from latitude and climatic data of the site, the program calculates solar energy impinging on each surface of the physical system and its energy flow is associated with the affected nodes (Collares-Pereira & Rabl, 1979; Lazzarin, 1981). The instantaneous values of the two radiation’s components, direct from Sun and sky diffuse, are calculated tacking into account any shading effects. The part of impinging radiation due to mutual diffuse reflections between surfaces is calculated solving an equation system. A similar process is used in the luminous field to calculate the illuminance value on each surface and the luminance of it (Cucumo et al., 1997).

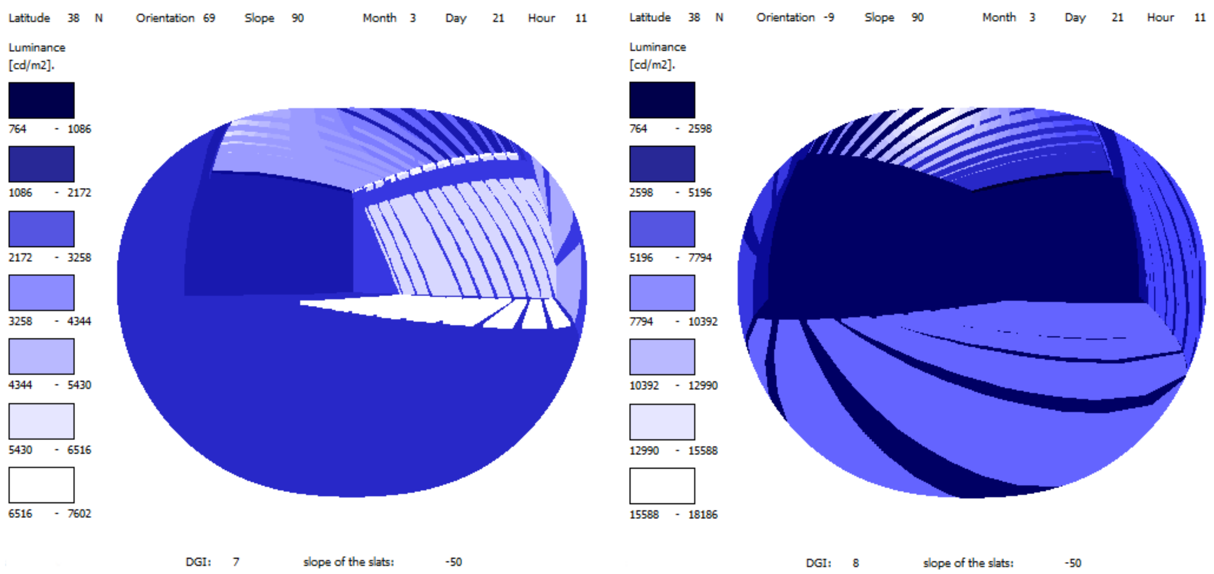

Figure 7: Samples of output of the algorithm used to calculate DGI or UGR indexes, in different positions in the courtyard

The calculation of DGI and UGR indexes values are performed by means of an algorithm that simulates the human field of view, and uses the calculated luminance values of each point of it (Luckiesh & Guth, 1949; Peterbridge & Longmore, 1954). The field of view is delimitated according to the indications of Professor H. M. Traquair (Traquair, 1938) (Figure 7).

The method should be completed with an analysis of the entire life cycle (LCA) of the intervention.

4. FIRST RESULTS

In the following evaluations, the average temporal presence of thirty people, with their sensible and latent thermal loads, has been assumed. When the courtyard is served by an HVAC system, it is assumed that it provides the required renewal air flow of 15 m^2/hour per person. When the court is only partially confined and without an HVAC system, two possible ventilation rates, depending on different wind speeds, were simulated. They are respectively of one and three total air changes per hour.

4.1. Thermal and luminous comfort

The assessment of both thermal and luminous comfort conditions was carried out with reference to four possible positions of an occupant in the courtyard. These positions are in four different areas, near the four corners of the courtyard at a distance of about two and a half meters from the walls.

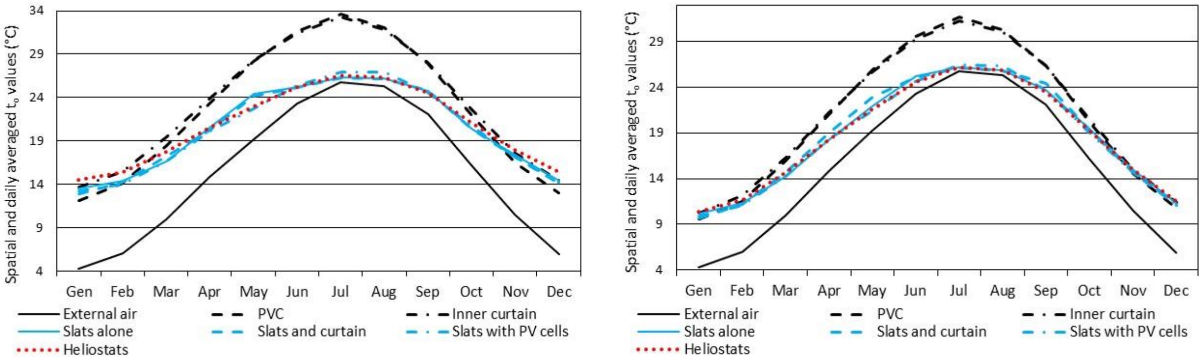

Figure 8: Venice. Spatial and daily averaged operative temperature (t_o) values in monthly typical days, in absence of HVAC system, with different solar control strategies. With a ventilation rate of one (on the left) and three (on the right) total air changes per hour

Without HVAC system, solar control strategies based on mobile slats or heliostats provide operative temperature (t_o) values closest to those of comfort, especially in the hottest period, when the translucent roof in PVC and the roof in glasses with internal curtains cause greater overheating (Figure 8 and 9).

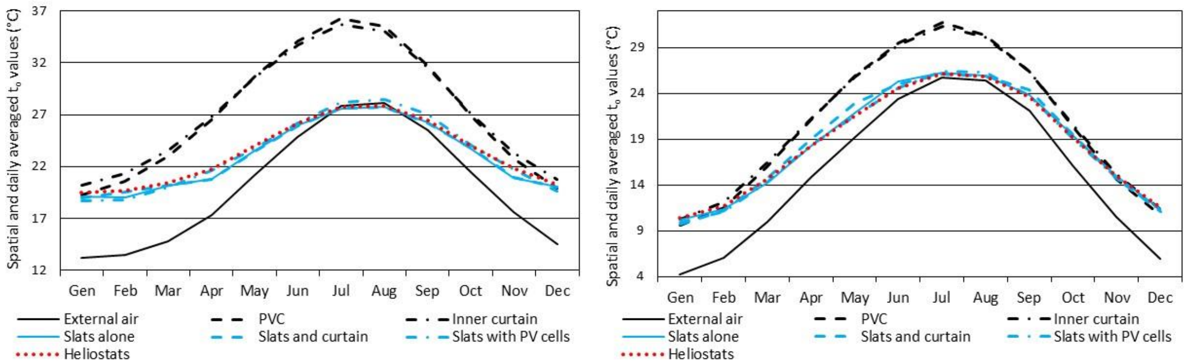

Figure 9 Palermo. Spatial and daily averaged operative temperature (t_o) values in monthly typical days, in absence of HVAC system, with different solar control strategies. With a ventilation rate of one (on the left) and three (on the right) total air changes per hour

Mobile slats and heliostats also provide better conditions of visual comfort.

The comparative assessment of luminous comfort has been conducted only for the devices that do not include the permanent presence of a diffuser, which should eliminate any type of glare, therefore only for the internal mobile curtain and the various types of slats.

The graphs in Figure 9 show the percentage frequency of the occupant-hours of visual comfort and discomfort on the total hours of use, which are found, in the absence of HVAC, after the actions aimed at thermal control and before the actions aimed at controlling glare.

The differences between the two strategies based on the slats are because they modify the incoming radiation differently. Therefore, the internal surface temperatures and the inclination of the slats which optimizes the t_o at the next hour are also modified.

Discomfort glare from extended light surfaces is evaluated by calculating the DGI index. Given the location of the extended light source (sky) in the upper part of the field of view, this type of discomfort never occurs and the DGI values are always within the limits. Instead, may occur discomfort due to the presence of direct radiation on a hypothetical visual task of the occupants (e.g. reading a newspaper at a bar table) (Robbins, 1986). This type of discomfort is more frequent in the absence of slats (Figure 10).

In both locations examined, the control actions aimed at maintaining visual comfort do not reduce the number of hours of possible daylighting.

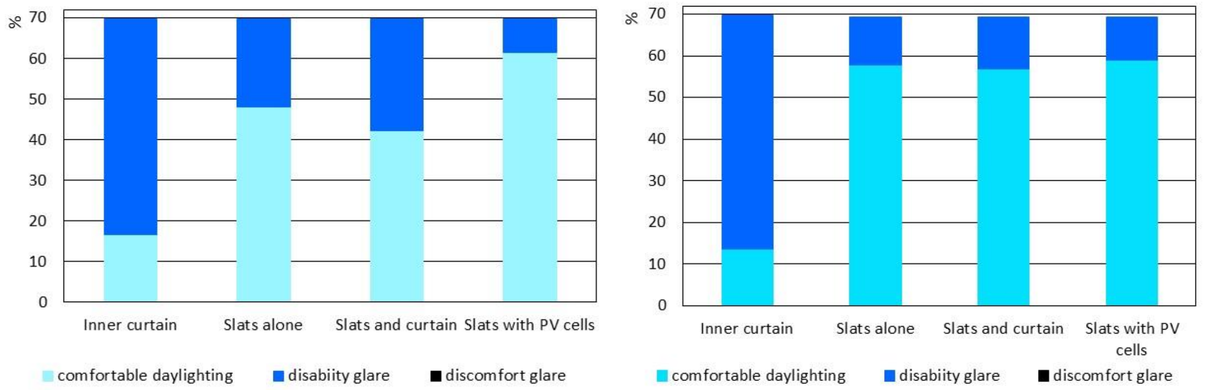

Figure 10: Percentage frequency of occupant-hours of visual comfort and discomfort on the total occupant-hours of use with the various solar control strategies, in Venice (on the left) and Palermo (on the right)

In Palermo, the number of hours of comfort is greater. This is because, given the greater intensity of solar radiation, the slats can intercept a larger fraction of radiation while still allowing an adequate internal illuminance (Figure 10).

4.2. Energy demand

If the covered space is served by an HVAC system, from the energy point of view, the worst solution is the fixed semi-transparent roof in PVC, mainly due to the higher energy demand for cooling that it entails. The roof in glasses with movable internal semi-transparent and diffusing curtains improves the results a bit and can allow the vision of the sky. The external slats are much more convenient, primarily because they control overheating better. The slats not combined with an internal diffuser or PV cells are the most convenient, but the differences are not relevant.

The opaque roof with heliostats is the more convenient solution. In fact, its transmittance is much lower than that of the other roofs examined, and this saves especially on heating (Figure 11).

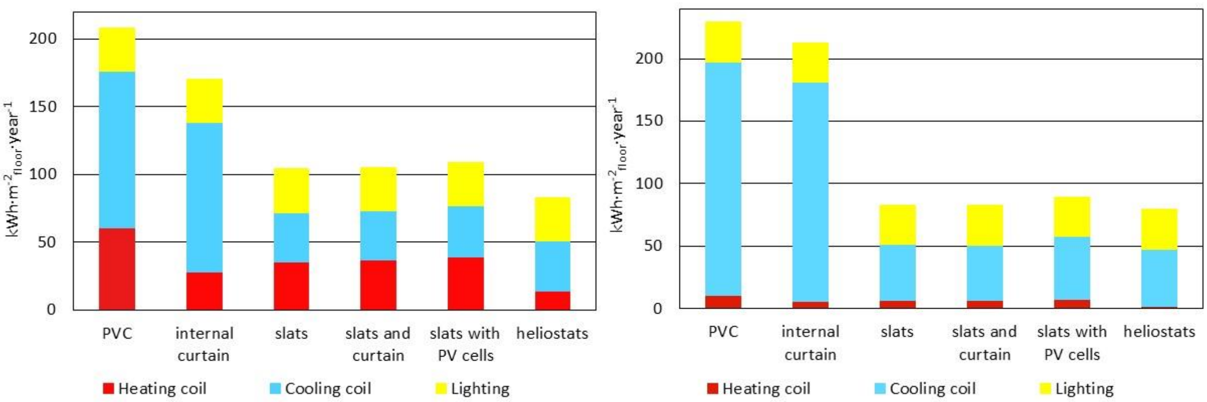

Figure 11: Annual specific primary energy demand (per square meter of floor area) for heating and cooling coils of the air-handling unit of the HVAC system and for lamps, with various solar control devices. In the climate of Venice (on the left) and Palermo (on the right)

If PV cells are added to the slats, or to the opaque roof equipped with heliostats, the courtyard can export electricity. If the slats are inclined in order to maximize PV production, while still ensuring daylighting when possible, the consumption of the HVAC system increases a little, but the electricity produced largely compensates for this higher cost.

5. CONCLUSION

The results of the simulations provide some useful design recommendations.

From the point of view of energy and comfort, it is advisable to limit the transparent part of the roof and insulate the opaque part, in order to limit winter heat losses and excessive solar gains in other periods.

Dynamic solar control devices, as external movable slats, are advisable on the transparent part of the roof. Compared to the semi-transparent roof, and the transparent roof equipped only with internal mobile curtains, they allow a considerable improvement in thermal and luminous comfort. Moreover, if the court is equipped with a HVAC system, they also allow considerable energy savings.

The use of a smaller transparent roof area served by heliostats allows further energy savings, and further improves winter thermal comfort. Unfortunately, this choice prevents the vision of the sky.

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