Vol. 01 (2025) 22-34, DOI: 10.61552/EC.2025.002

Energy Catalyst

www.jme.aspur.rs

Environmental Control of Urban Covered Courtyards in Mediterranean Climates – Comparison between different strategies

Antonio Carbonari[a,*], Massimiliano Scarpa[b], Francisca Ignacia Méndez Plaza[c]

[a]*University IUAV of Venice, Cannaregio 4030, 30121 Venezia, Italy,*
[b]*University IUAV of Venice, Dorsoduro 2206, 30123 Venezia, Italy,*
[c]*Freelance Architect, Las Condes, Santiago, Chile.*

Keywords:

Covered courtyard, Temperate Climates, Environmental control, Thermal and visual comfort

* Corresponding author:

Antonio Carbonari
E-mail: antoniocarbonari7@gmail.com

Received: 18 March 2025
Revised: 20 April 2025
Accepted: 2 May 2025

A B S T R A C T

Covering urban courtyards allows the creation of pleasing public or semi-public spaces, sheltered from bad weather and possibly with a controlled climate. The use of transparent or semi-transparent roofs, that allow daylighting, is a common solution in central and northern Europe, but not in Mediterranean climates, where it would cause overheating for a good part of the year in the absence of appropriate solar control strategies. The case study examined in this work is the courtyard of a former Venetian convent. With reference to it, by means of computer simulations, some types of partially transparent roofing and some solar control strategies were compared from the points of view of energy demand, thermal and visual comfort. Given the diffusion of this type of courtyards in the Italian territory, the simulations were also performed using the climate data of the warmer climate of Palermo. The better solutions appear to be those based on the use of dynamic solar control devices.

1. INTRODUCTION

Covering urban courtyards allows the creation of pleasing 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. The coverage of these spaces can extend their use throughout the year. The adoption of transparent or semi-transparent roofs, that allows the use of daylighting, is a common solution in the countries of central and northern Europe [1,2]; but it is difficult to apply it in temperate Mediterranean climates, where it would cause overheating for most of the year. This can happen if appropriate design measures are not adopted to control the incoming solar radiation through the roof [3,4]. In fact, these climates are often characterized by cold winters and hot-humid summers therefore solar gains can be useful or harmful depending on the seasons, so the optimal fraction of coverage that can be made transparent is variable throughout the year. Its oversizing could result in high thermal losses in winter and overheating in the rest of the year, while its undersizing would penalize daylighting and thermal solar gains during the heating period. Therefore, it is advisable to explore the possibility of using variable extensions of the transparent area by means of appropriate solar control devices, e.g. curtains, movable slats or more complex daylighting systems. It is probably for these reasons that the topic of climate control of such spaces in temperate climates has not been studied much, most of the existing studies are focused on cold or hot climates [5,6].

In this work, a case study on this topic was taken into consideration; it consists of the courtyard of the former convent of San Pietro di Castello (Figure 1), in the city of Venetia in northern Italy (45.5° N, 20 °C-base heating degree-days equal to 2345). Currently the buildings that surround the courtyard are used as dwellings. With reference to it, the introduction of a partially transparent roof has been hypothesized, and various solar control strategies were compared from the points of view of primary operational energy demand, thermal and luminous comfort [**7**].

The study was performed only by means of unsteady state building energy simulations, using a specific homemade software. The software operated on a simplified digital model of the courtyard. In formulating solar control strategies, the criterion of optimizing the conditions of thermal and luminous comfort has been adopted, guaranteeing daylighting as long as possible. It has also been hypothesized that the courtyard could be equipped with an internal environmental control system; in this case, the solar control strategy was also aimed at minimizing its primary energy demand. Given the diffusion of this type of courtyard in Italian territory, its thermal and luminous behaviour has also been simulated using data of the warmer climate of Palermo, in Southern Italy (38.11° N, 20 °C-base heating degree-days equal to 751).

The comparison between the various strategies concerned the performance regarding thermal, visual comfort and the primary operational energy demand for artificial lighting and environmental control.

Fig. 1. Some images of the examined courtyard. Images source: Google Earth and authors [7].

Simulations results provide some design indications, but for a more holistic evaluation the method would require integration with appropriate tools for the assessment of the entire life cycle of the intervention (LCA).

2. THE CASE STUDY

The courtyard of the former convent examined has the major axis oriented approximately in a north-south direction; the church is located on its north side. The courtyard is bordered by buildings of the sixteenth century with structural internal and external brick walls, 0.35 m thick, plastered on both sides; therefore, 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 heat capacity (C_{front}) is about: 640 $kJ \cdot m^{-2} \cdot K^{-1}$. Windows occupy approximately 10% of the façade surface (Figure 2), it has been assumed that the windows are equipped with double glazing and a wooden frame (a typical solution of building renovations of the eighties of the last century.), with U-value equal to 1.69 $W \cdot m^{-2} \cdot K^{-1}$ (see Table 1). It has also been assumed that the interiors of these buildings are maintained in every season at the comfort temperatures by means of their systems. According to Italian legislation these comfort temperatures are 20 °C in winter and 26 °C in summer, while in mid-season they have been assumed to be equal to the average daytime external temperature, since the clothing of the occupants is adapted to it. The relative humidity set point is assumed to be equal to 50% all over the year.

Fig. 2. A building prospectus in the courtyard. Images source: authors [7].

The digital model used in the simulations is simplified from the geometric and thermo-physical point of view; it includes the proposed roof, the walls of the buildings delimiting the courtyard and the ground of the same. The pavement of the courtyard consists of a layer of stones about 0.15 m thick. In the thermo-physical model, a 0.5 m thick layer of soil was included. The total front heat capacity of these layers (pavement and underlying soil) was estimated equal to 3704 $kJ \cdot m^{-2} \cdot K^{-1}$ and its U-value equal to approximately 1.65 $W \cdot m^{-2} \cdot K^{-1}$.

With reference to this courtyard, the inclusion of a partially transparent roof has been hypothesized, and various solar control strategies were compared. The roof is schematically represented in Figures 3 and 4, where, in addition to the pillars, they are visible vertical ducts that have the function of evacuating rainwater.

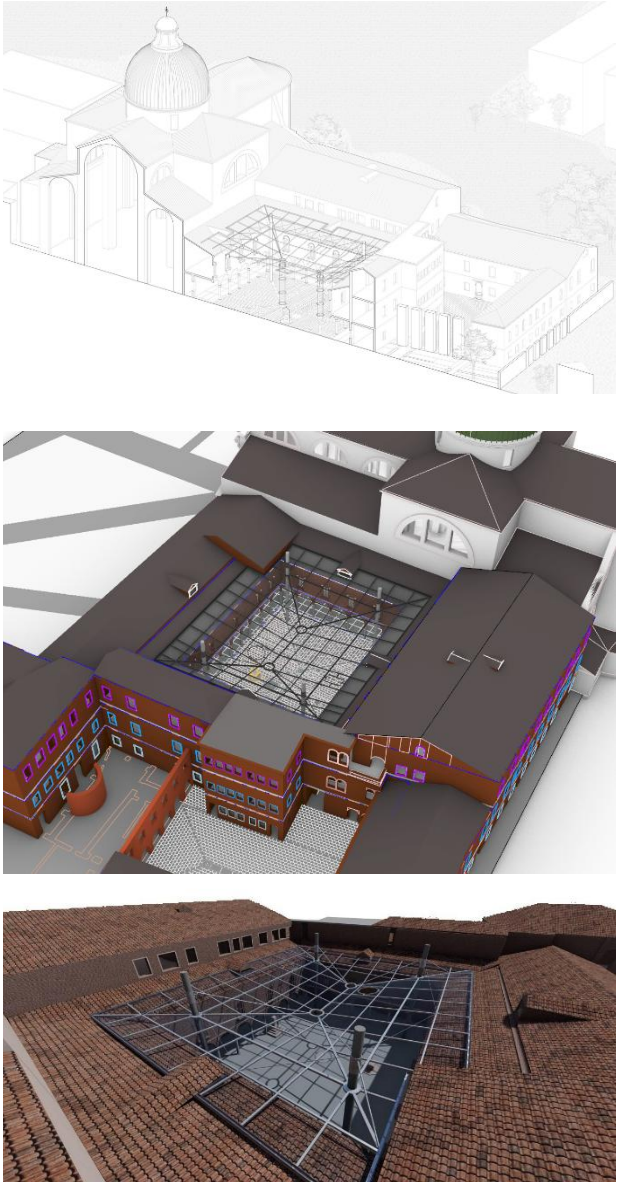

Fig. 3. Schematic representation of the hypothesized roof. Image source: authors [7].

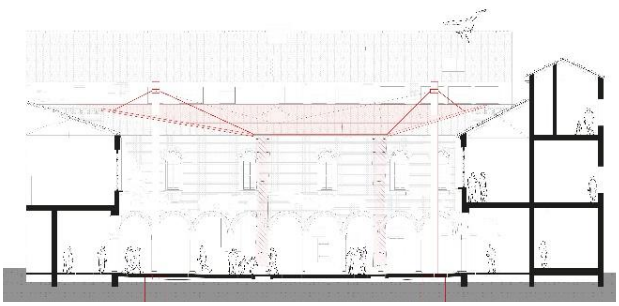

Fig. 4. Section of the courtyard with the hypothesized roof Image source: authors [7].

In the first phase of this study, only a partial confinement of the courtyard and the absence of any mechanized heating, ventilation and air conditioning system (HVAC) were hypothesized. Therefore, the various design 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 supposed that the lighting plant is switched on when the average natural illuminance in the courtyard is less than 300 lx. Afterward, 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 the HVAC 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), its coefficient of transparency is assumed to be equal to 0.5,
- 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. The coefficient of transparency of the curtain is assumed to be equal to 0.5, while its internal and external reflection coefficients are equal to 0.43, both in energy and light field. The curtain is mobile and is used when necessary to avoid glare phenomena and to reduce the solar gains (e.g. courtyards of California Institute of Sciences in San Francisco or Sony Center in Berlin),

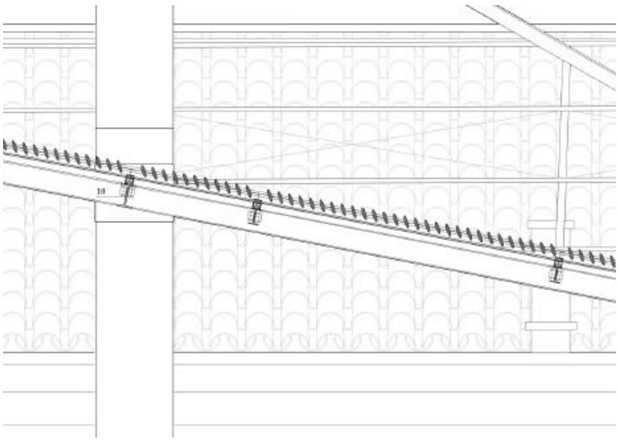

Fig. 5. Section of the roof in glasses with external mobile slats. Image source: authors [7].

- the same transparent roof described in the previous point with the addition of an external mobile slats system (Figure 5). Slats are controlled to minimize energy demand for internal environmental control, if the HVAC system is present, and optimize thermal and visual comfort (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 to minimize energy demand, if the HVAC system is present, 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 6 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.

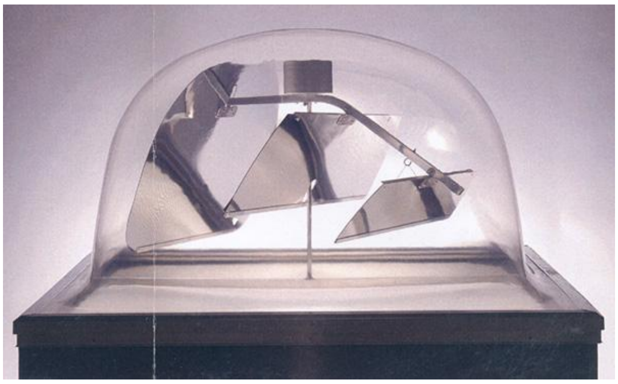

Fig. 6. Sample of heliostat, system "Lux tracker". From catalogue of Lux Service Lucernari s.r.l. http://www.luxservice.it/.

The possibility of inserting photovoltaic (PV) cells on the mobile slats, occupying 80% of their surface, and on the 60% of the opaque roof equipped with heliostats was also explored, in this second case, the PV cells are not tiltable but are arranged according to an optimal fixed inclination. Based on our previous study, this inclination has been assumed to be equal to 30°, for south-facing panels, both in Venice and Palermo [8].

Table 1 shows the average surface values of transmittance (U-value) and front heat capacity (C_{front}) of the building elements delimiting the courtyard and possible coverages.

Table 1. Main thermal characteristic of the building elements delimiting the courtyard.

Building element	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

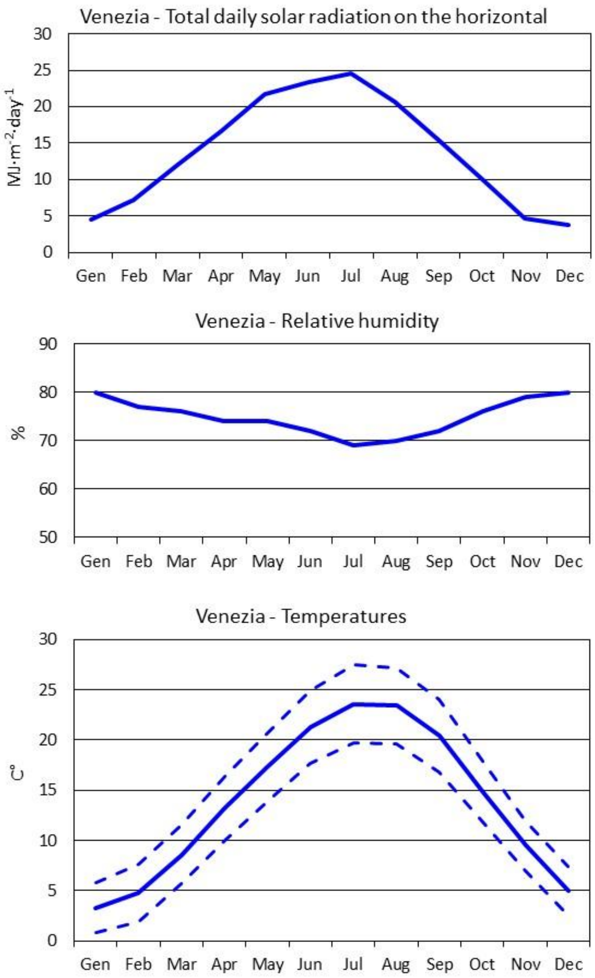

Fig. 7. Climate data of Venice and Palermo.

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 type of solar control devices. In the configuration that requires the most power, which is the one with the translucent 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.

In Figure 7 and 8 are reported the climatic data of the two examined locations.

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, gas-boilers integrate this supply when necessary.

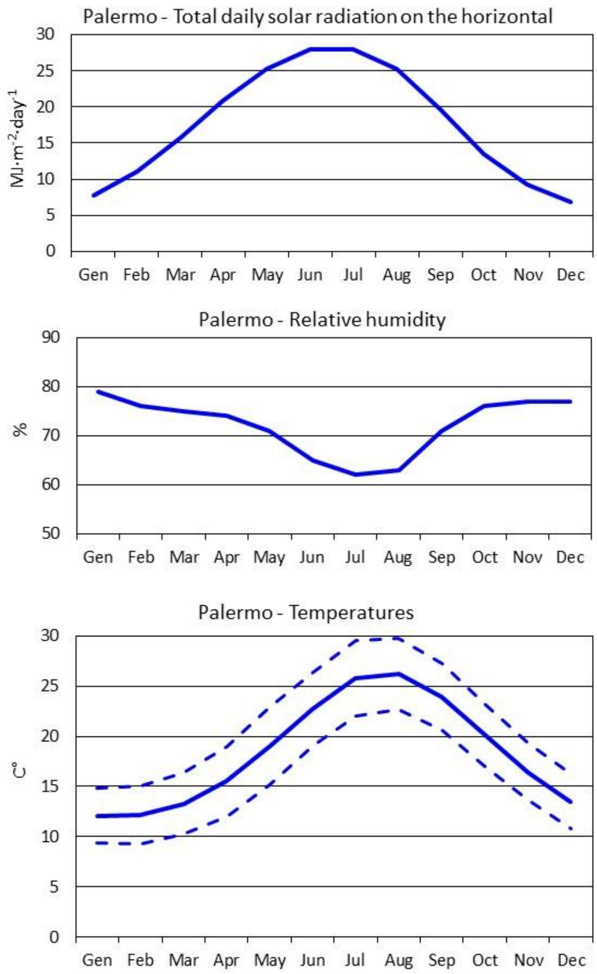

Fig. 8. Climate data of Venice and Palermo.

The chillers have a nominal coefficient of performance (COP) equal to 4.5, while boilers have an efficiency of 0.9, they are modified in each calculation step according to the part load ratio. The primary energy conversion coefficients are 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.

The hypothesized light system consists of fluorescent lamps with a luminous efficiency of 91 lm/W and a total power of 3 kW.

3. METHODS

Usually, this type of analysis is carried out using different software to simulate the thermal and luminous behaviour of the building separately, these are software like: EnergyPlus, for energy simulation, and Radiance, for lighting simulation. 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 [9,10]. It is mainly aimed at supporting the design of solar control devices and related control logics. It takes into consideration the physical system composed by a room, with the typical dimensions of that of an apartment or an office, its glazed surfaces, internal and external solar control devices (e.g. slats, blinds, overhangs, and any element shading the glazed surfaces) as well as the surrounding urban environment. Urban context includes the building containing the examined room. The program simulates the dynamic thermal and luminous behaviour of the physical system at hourly time steps, and provides sensible and latent thermal loads, primary energy demand for HVAC and artificial lighting, evaluation of thermal and visual comfort. To do this it performs a thermal balance and a light simulation of the room with hourly calculation step.

To perform the thermal balance of the physical system 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, slab or a glass plate): a thermal grid model [11-14]. This algorithm provides the thermal flows between the nodes and their temperatures (see the Appendix 1).

At present only one node, in the center of the room, represents the air mass. To use more air nodes, it would be necessary to sophisticate the model with a fluid-dynamic part (CFD), which is currently absent for the reasons set out above. In this study *Ener_lux* is used for the first time to study a large room.

Currently the software in its entirety has not been validated but the part of it that performs the dynamic thermal balance contains an algorithm developed at University IUAV of Venice in the early 80s as part of the second Energy Finalized Project (PFE2) of the National Research Council (CNR). This algorithm (called "Midas") had been validated with field measurements on an experimental passive building [15,16].

The calculated temperature values of the nodes corresponding to the internal air and internal surfaces are also used to calculate thermal comfort indices. These indices are the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [17], that are adopted by the Italian standard [18]. The plane radiant temperature asymmetries values are also calculated.

Urban obstructions and any external shading elements must be described only from geometrical and radiative point of view. At present the internal furnishing elements are described in a simplified way, as well as the external elements because they are not included in the thermal grid model, but they interact with energy and luminous radiation entering the confined space under examination and exchanged between the internal surfaces.

Other input data are information on the use of the room, number and kind of occupants, internal sensible and latent thermal sources, time profile of use, type of systems.

The primary energy demand is calculated considering the sensible and latent thermal loads and the type of HVAC system. Efficiency of the plant is calculated in each time step tacking into account the load factor. In the current software's version, the hourly values of climate data are derived from the daily data normally available.
Starting from latitude and climatic data of the site, the program calculates Sun's position and solar energy impinging on each surface of the

physical system and the relative energy flow is associated with the affected nodes of the thermal grid model. International known algorithms are used for calculating the instantaneous values of two radiation's components: direct from Sun and sky diffuse [19,20]. They are calculated tacking into account any shading effects, for any surface the profile of the part exposed to direct radiation is calculated by means of a projective algorithm. The total radiation affecting each surface also includes a part due to mutual reflections between the surfaces constituting the system, it is calculated by solving a system of linear equations [21], see the Appendix 2.

Generally, the reflections are diffused, in case of specular reflections due to particular devices, as polished slats surfaces, the program calculates the intensity of the first mirrored radiation and traces its path; it is assumed that the following reflections are diffused. The mirrored energy is handled as the direct component of the radiation.

A similar process is used in the luminous field to calculate the illuminance value on each surface and the luminance of it. Relatively to each surface IESNA and CSTB algorithms are used to calculate illuminance due respectively to direct solar radiation and sky [22]. System's solution in this case provides the luminous radiance value of each surface, from which the luminance value can be easily derived in case of diffuse reflections. Starting from the luminance values, the program builds a model of the occupant's visual field where the luminance of each point is represented (Figure 9).

The field of view is delimited according to the indications of Professor H. M. Traquair [23]. The algorithm calculates the solid angles subtended by the light sources and corrects them, when required, by the Guth position index [24,25]. In this way, visual comfort is evaluated by calculating the following indices:

- Daylighting Glare Index (DGI) in case of wide light sources [26], this index is adopted by the Italian standard [27],
- Unified Glare Rating (UGR) in case of smaller ources [28,29],
- uniformity factor of the internal illuminances value (U_o) [30],
- a check on disability glare [31] is also performed.

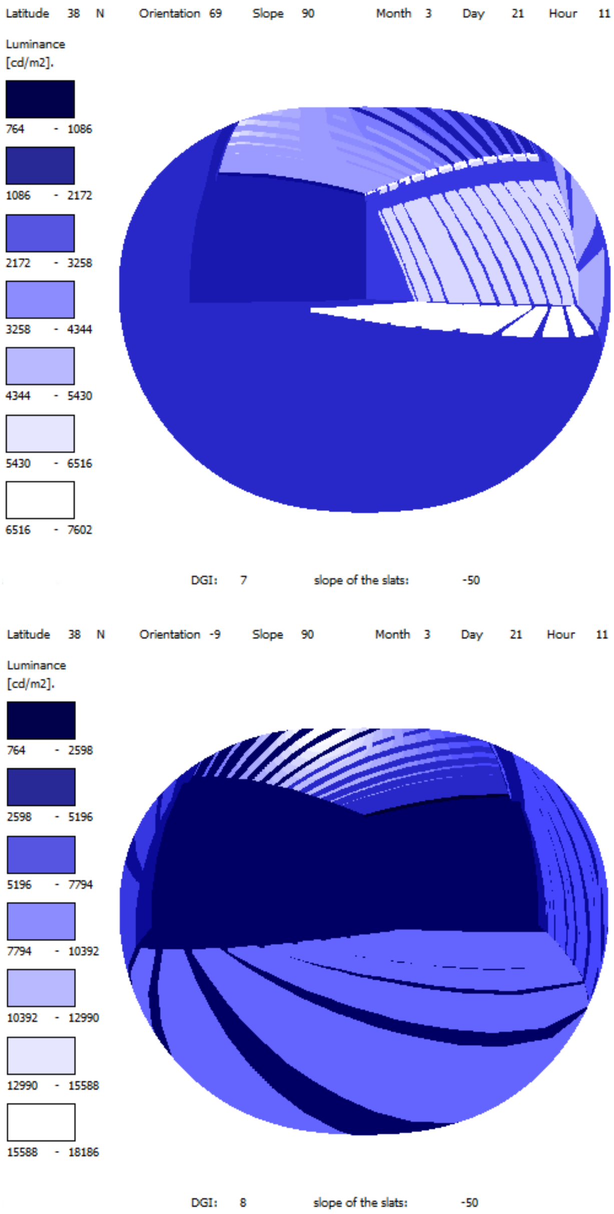

Fig. 9. Samples of output of the algorithm used to calculate DGI or UGR indexes, in different positions in the courtyard. The geometric model of the roof is simplified.

Controls on visual comfort are performed only when the lamps are turned off. If the illuminance value on a visual task is not sufficient it is assumed that the lighting system is activated, and the related heat flow is included in the room's heat balance. It is possible to consider the plant's zoning and luminous flow control by dimmer.

Within each calculation step, the program checks the conditions of thermal and luminous comfort relatively to some significant position of occupants inside the room by calculating the indices mentioned above. These positions must be chosen in the instruction phase of the program.

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

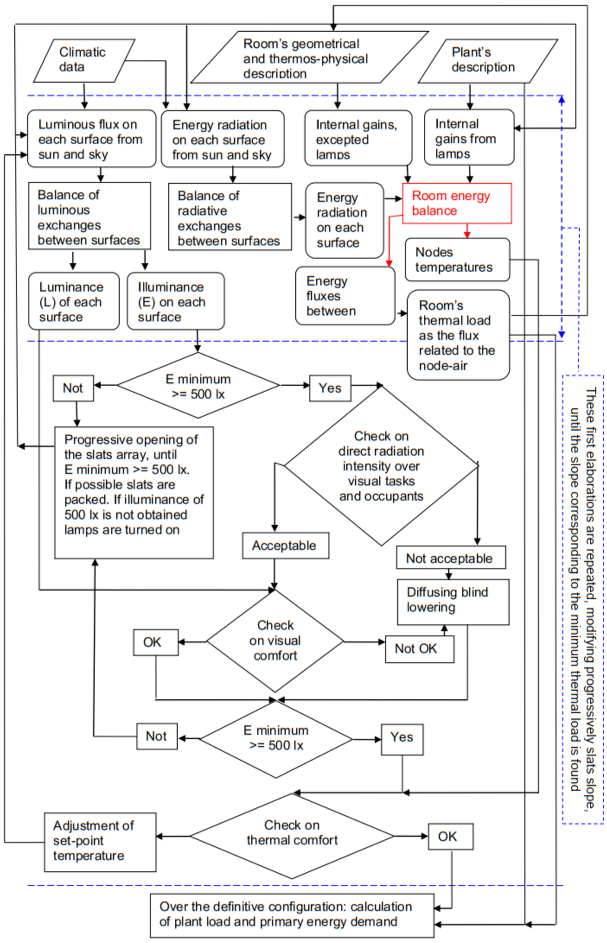

Fig. 10. Flowchart of the software used, when simulating a solar control system including external slats and internal curtain.

If visual or thermal discomfort conditions are detected any necessary feedback on the solar control devices and/or on the set-point temperatures of the HVAC system, if there is, is automatically simulated and the calculation of the hourly time-step is repeated.

If adjustable devices are present, all the solar control actions, such as slats tilting or screen lowering, are simulated by modifying the digital model, and all the elaborations are repeated iteratively until the comfort conditions are achieved. When the comfort conditions are reached the program calculates the primary energy demand for HVAC and artificial lighting (Figure 10).

Therefore, these results allow some assessments regarding the primary energy demand, the thermal and visual comfort, but for a more general evaluation of each design solution it would be useful to combine this software with appropriate tools for the assessment of the entire life cycle of the intervention (LCA).

4. FIRST RESULTS

In the simulations, the average temporal presence of thirty people, with their sensible and latent thermal loads, has been hypothesized. When the courtyard is served by an HVAC system, it is assumed that it provides the required renewal air flow of 15 $m^2 \cdot hour^{-1}$ per person. When the courtyard is only partially confined and not equipped with an HVAC system, two possible natural ventilation rates, relative to two possible wind speeds outside, were simulated; they are respectively 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 about two and a half meters from the walls.

In the absence of HVAC, solar control strategies based on mobile slats or heliostats provide the operative temperature (t_o) values closest to those of comfort, especially in the hottest period, while the translucent roof in PVC and the roof in glasses with internal curtains cause greater overheating (Figure 11 and 12).

In a physical configuration such as that of the case study, devices that include the permanent presence of a diffusing element can eliminate any type of glare, therefore the comparative assessment of luminous comfort was made only with reference to the devices that do not include them: the glazed roof with internal rolling curtain and the various types of slats.

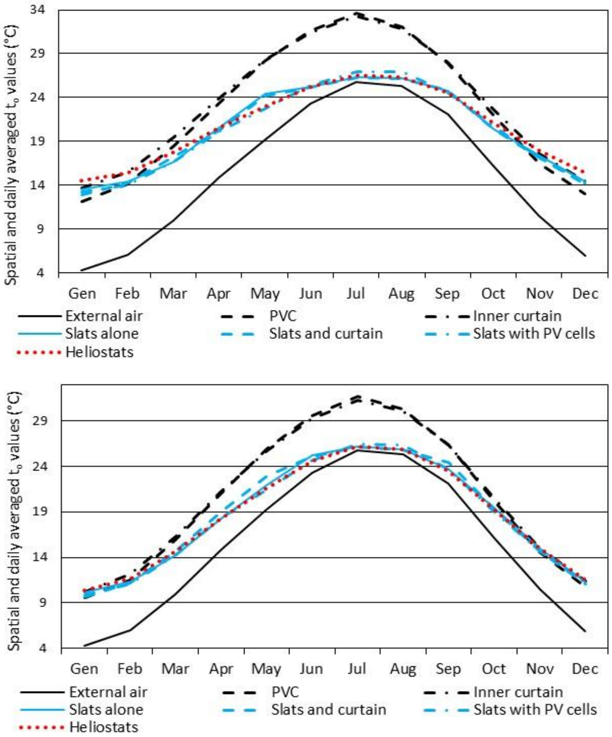

Fig. 11. Venice. Spatial and daily averaged operative temperature (t_o) values in monthly typical days, in absence of HVAC system, with different solar control strategies. With a ventilation rate of one (above) and three (below) total air changes per hour.

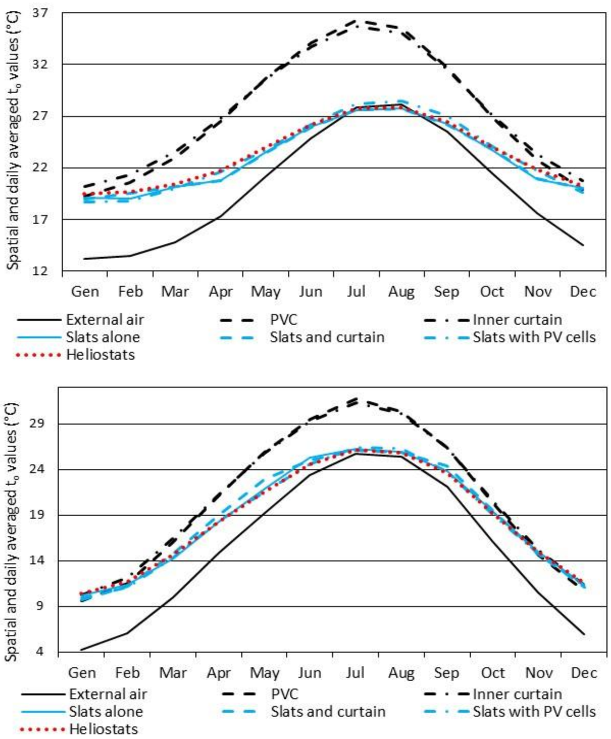

Fig. 12. Palermo. Spatial and daily averaged operative temperature (t_o) values in monthly typical days, in absence of HVAC system, with different solar control strategies. With a ventilation rate of one (above) and three (below) total air changes per hour.

The histograms in Figure 13 show the percentage frequency of the occupant hours of visual comfort and discomfort, on the total hours of use. This is in the absence of HVAC, after the actions aimed at thermal control and before the actions aimed at controlling glare.

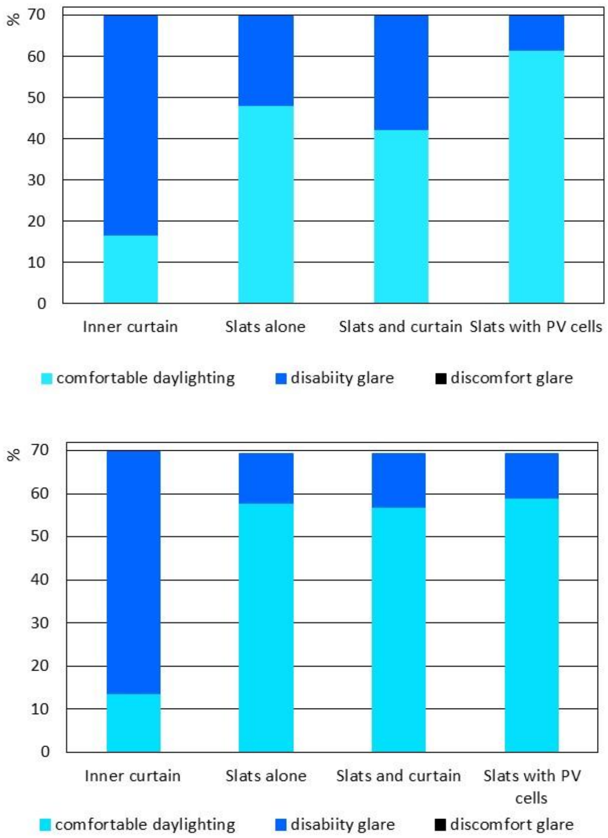

Fig. 13. Percentage frequency of occupant-hours of visual comfort and discomfort on the total occupant-hours of use with the various solar control strategies, in Venice (above) and Palermo (below).

The strategies based on the use of mobile slats modify the incoming radiation to different degrees, therefore the internal temperatures and slats slope optimizing the operative temperature in the following hours are different.

The only type of visual discomfort that occurs in the case study is the disability glare due to direct radiation on a hypothetical visual task of the occupants (e.g. reading a newspaper at a bar table) [31]. In fact, the extended light source (the sky) is in the zenith position, in the upper part of the occupant's visual field, therefore the discomfort glare from extended sources never occurs, and the values of the DGI are always within the limits. Understandably the disability glare is more frequent in the absence of slats.

In both locations examined, the control actions aimed at maintaining visual comfort do not reduce the number of hours of possible daylighting. In Palermo the greater intensity of solar radiation means that the slats can intercept a greater fraction of direct solar radiation while still allowing an adequate internal illuminance, therefore the number of hours of comfortable daylighting is greater.

4.2 Energy demand

If the climate in the courtyard is controlled by an HVAC system, the fixed semi-transparent roof in PVC is the most energy-consuming solution, mainly because of higher energy demand for cooling. The roof in glasses with movable internal semi-transparent and diffusing curtains offers slightly better results: compared to PVC roof its total primary energy demand is 18% lower in Venice, 7% in Palermo.

The solutions based on external slats are much more efficient in reducing total energy demand, primarily because they control overheating better, in general in Venice for all the configuration with slats the total energy demand is the half of those of roof in PVC. In particular, if we do not consider the production of photovoltaic electricity, the slats not combined with an internal diffuser or PV cells (therefore not inclined in order to maximize the energy production of any PV cells) are the most convenient, but the differences respect to the other solution with slats are not relevant (less than 2.5 percentage points). These savings are about 64% in the climate of Palermo for the slats without PV cells, and 60% for those with PV cells.

The opaque roof with heliostats is the solution that offers the lowest energy consumption: 60 % lower respect to the roof in PVC in Venice and 65% in Palermo. In fact, its transmittance is much lower than that of the other roofs examined and this reduce especially energy demand for heating (Figure 14 and 15).

As shown in the figures, all these differences are more marked in the climate of Palermo, where the PVC solution is more disadvantageous than the others, especially due to the higher energy demand for cooling.

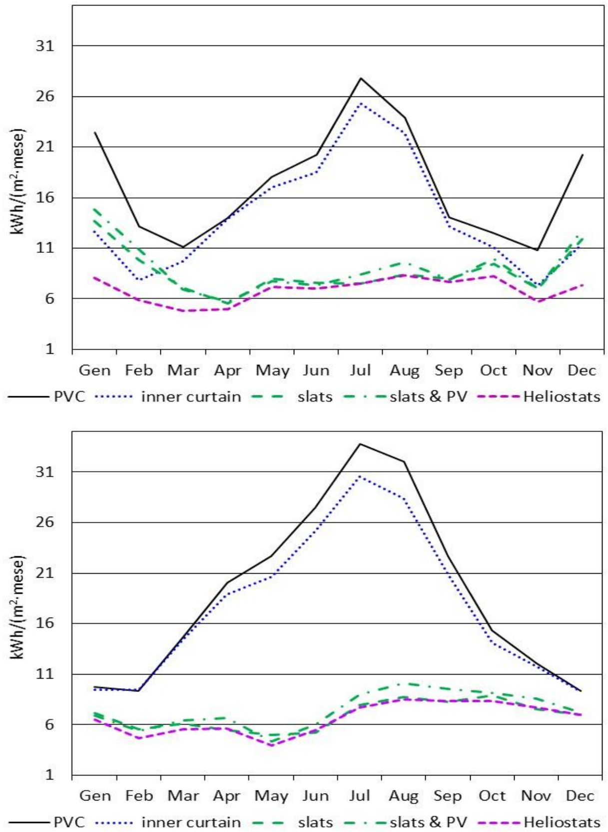

Fig. 14. Monthly specific primary energy demand (per square meter of floor area) for heating and cooling coils of the air-handling unit of the HVAC system and for lamps, with various solar control devices. In the climate of Venice (above) and Palermo (below).

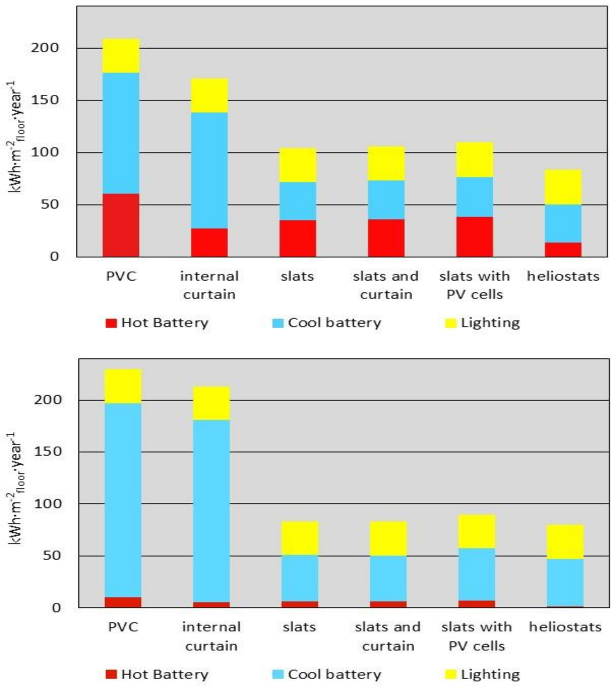

Fig. 15. Annual specific primary energy demand (per square meter of floor area) for the same uses of Figure 14, with various solar control devices. In the climate of Venice (above) and Palermo (below).

If the slats or the opaque roof with heliostats are equipped with PV cells, the courtyard can export electricity. In terms of primary energy equivalent, when the slats are equipped with PV cells and are controlled with the logic of maximizing their production, the electricity produced annually is equivalent to about 3.74 times the total annual energy demand of the courtyard (for HVAC and artificial lighting) in Venice, 5.7 times in Palermo.Instead, the electricity generation of the fixed PV cell located on the roof correspond to 4.23 times the total energy demand in Venice and 5.5 times in Palermo. The electricity produced by the PV cells located on the roof is lower in absolute value than that of the cells mounted on the slats, because on the roof the PV cells occupy a smaller surface area and are not tiltable, but the energy demand of the courtyard is lower.

The primary energy values corresponding to photovoltaic production are not represented in the figures for reasons of scale.

If the slats are inclined in order to maximize PV production, while still ensuring daylighting, the consumption of the HVAC system increases a little, due to higher solar gains, but the electricity produced largely compensates for this higher cost.

5. CONCLUSION

In temperate Mediterranean climates, environmental control of covered urban courtyards requires strategies that can adapt to very different seasonal conditions. This is to avoid overheating in most of the year and ensure daylighting as long as possible even in the cold period. In this work, various solutions were compared by means of computer simulations, using specific homemade software. The comparison concerned aspects relating to operational energy demand, thermal and visual comfort. From these points of view, the results of the simulations provide some useful design recommendations.

- In general, limiting the transparent part of the roof and insulating its opaque part reduces winter heat losses and excessive solar gains in other periods. Therefore, by adopting this criterion it is possible to reduce the energy demand for heating, ventilation and air conditioning, if a HVAC system is present, and improve the general conditions of comfort, both thermal and visual.
- Dynamic solar control devices external to the transparent part of the roof, such as movable slats, seem to be a much more performing solution. 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 during the year. Moreover, if the courtyard is equipped with a HVAC system, they also result in significantly lower energy demand, compared with the case of PVC roof the energy saving is around the 50% in Venice and the 64% in Palermo, even 60% in the case of the slats with PV cells in Palermo.
- The design solution based on a smaller transparent roof area served by heliostats allows further energy savings, about 60% in Venice and 65% in Palermo, and further improves winter thermal comfort. Unfortunately, this solution does not allow the view of the sky.
- If the slats or the opaque roof with heliostats are equipped with PV cells, the courtyard can export electricity. In both climates examined, the PV cells arranged on tilting slats give better performance than the fixed ones arranged on the opaque roof of the solution with heliostats.

However, in practice, the design choices are also greatly influenced by other aspects, such as monetary costs and a more general assessment of the environmental impact of the intervention. The simple PVC roof, for example, while providing the lowest performance from the point of view of operational energy demand and thermal comfort, would require easier maintenance and have less embodied energy than other solutions. It also has a lower initial monetary cost.

It would be necessary to compare these advantages with the disadvantages due to the higher consumption of primary energy from non-renewable sources over the entire life cycle of the various interventions. Therefore, the method for evaluating the various strategies should integrate tools for the assessment of the entire life cycle of the proposed devices (LCA tools).

APPENDICES

1. Each elementary zone constitutes a node of the thermal grid and must be described from geometrical and thermophysical points of view: density, conductivity and specific heat capacity have to be defined as well as the following surfaces radiative properties: infrared emissivity, diffuse reflection coefficient and specular reflection coefficient. These last two coefficients are used to describe surface's behaviour toward solar radiation: the first represents the fraction of impinging energy that is globally reflected, the second represents the fraction of reflected energy that is redirected in a mirror like way. Both of these coefficients can assume two different values: one is relative to total solar spectrum and the other only to visible range. The heat transfer coefficients between each node and the others must also be defined. For each node the program builds a heat balance equation, the solution of the system composed by all these equations provides the values of nodes temperatures and heat flows changed between the nodes. The room's sensible thermal load is obtained from these solutions: for instance, if an all-air system is simulated, the thermal load consists of the heat flow related to the node representing the room's internal air. In other cases, the thermal load consists of the heat flow related to the nodes associated with the system's terminals.

2. Each equation of this system represents a surface's radiative energy balance, in it the total radiation incident on the considered surface (unknown) is represented as its radiance divided by its diffuse reflection coefficient, the radiation from any other visible surface is represented by its energy radiance (unknown) multiplied by the relative view factor, while the radiation from the Sun and the sky, if present, are the known term. The view factors between the surfaces are calculated by an algorithm based on the unit-hemisphere method [32]. System's solution provides the energy radiance value of each surface, consequently the total radiation impinging on it. This value is associated to the node of the thermal grid that contains the irradiated surface.

REFERENCES

[1] U. Berardi and T. Wang, "Daylighting in an atrium-type high performance house". *Building and Environment*, vol. 76, pp. 92-104, Jun. 2014, doi: 10.1016/j.buildenv.2014.02.008

[2] A. Rymarov, "Energy saving in the formation of covered courtyards". In *Proc. EO-DOK 2019 - 11th Conference on Interdisciplinary Problems in Environmental Protection and Engineering.* Polanica-Zdroj, Poland 8th - 10th April 2019. A. Carbonari [Online]. Available: doi: 10.1051/e3sconf/201910000072

[3] A. Aldawoud, "The influence of the atrium geometry on the building energy performance". *Energy and Buildings*, vol. 57, pp. 1–5, Feb. 2013, doi: 10.1016/j.buildenv.2015.11.023

[4] R. Aram and H. Z. Alibaba, "Thermal Comfort and Energy Performance of Atrium in Mediterranean Climate". *Sustainability*, vol. 11, no. 4, pp. 1184-1213, Feb. 2019, doi: 10.3390/su11041213

[5] F. Wang, K. Pichatwatana, S. Roaf, L. Zhao, K. Zhu and L. Jingyan, 2014. "Developing a weather responsive internal shading system for atrium spaces of a commercial building in tropical climates". *Building and Environment*, *vol. 71*, pp. 259-274, Jan. 2014, doi: 10.1016/j.buildenv.2013.10.003

[6] M. Taleghani, M. Tenpierik and A. Van Den Dobbelsteen, "Indoor thermal comfort in urban courtyard block dwellings in the Netherlands". *Building and Environment*, *82*, pp. 566-579. Dec. 2014, doi: 10.1016/j.buildenv.2014.09.028

[7] F. Mendez Plaza, "Memoria e senso di un luogo storico dimenticato – Progetto architettonico di conservazione e restauro dell'ex palazzo di San Pietro di Castello". Degree thesis. Dept. Arch., Construction and Conservation, Univ. IUAV di Venezia, Venice, Italy, 2021.

[8] A. Carbonari and M. Scarpa, "Optimal Arrangement of Photovoltaic Panels Depending on Climate and Building's Intended Use" in *Proc. PLEA 2016 - 32th Conference, Cities, Buildings, People: Towards Regenerative Environments*, PLEA 2016 Los Angeles, Eds. Jul. 2016, pp. 493-499.

[9] A. Carbonari, "Thermal and luminous comfort in classrooms: a computer method to evaluate different solar control devices and its operating logics" in *Proc.PLEA 2012 - The 28rd Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture*, PUCP, Eds. Nov. 2012.

[10] A. Carbonari, "Solar control of extensively glazed facades: a computer method for predicting the effects of various devices and building's thermal inertia". In *Proc. SET 2017 – 16th International Conference on Sustainable Energy Technologies*, WSSET and Alma Mater Studiorum Università di Bologna, Eds. Jul. 2017, pp.

[11] A. Buonomano, G. De Luca, U. Montanaro and A. Palombo, "Innovative technologies for NZEBs: An energy and economic analysis tool and a case study of a non-residential building for the Mediterranean climate". *Energy and Buildings,* vol. 121, pp. 318–343, Jun. 2016, doi: 10.1016/j.enbuild.2015.08.037

[12] G. Fraisse, C. Viardot, O. Lafabrie and G. Achard, "Development of a simplified and accurate building model based on electrical analogy". *Energy and Buildings,* vol. 34, no. 10, pp. 1017–1031, Nov. 2002, doi: 10.1016/S03787788(02)00019-1

[13] J. H. Kämpf and D. Robinson, "A simplified thermal model to support analysis of urban resource flows". *Energy and Buildings*, vol. 39, no. 4, pp. 445–453, Apr. 2007, doi: 10.1016/j.enbuild.2006.09.002

[14] C. P. Underwood, "An improved lumped parameter method for building thermal modelling". *Energy and Buildings,* vol. 79, pp. 191-201, Aug. 2014, doi: 10.1016/j.enbuild.2014.05.001

[15] A. Fanchiotti, G. Rossi, C. Trevisan and M. Vio, *Sistemi Solari Passivi – Progettazione e realizzazione di una stazione di prova di muri trombe modello di simulazione numerica confronto tra dati sperimentali e risultati numerici*. Venezia, Italy: Istituto Universitario di Architettura di Venezia, 1983.

[16] A. Carbonari, A. Fanchiotti, G. Rossi and C. Trevisan, *Sistemi Solari Passivi 2 – Raccolta ed elaborazione dati dalla stazione di prova di muri di Trombe*. Venezia, Italy: Istituto Universitario di Architettura di Venezia, 1986.

[17] P. O. Fanger, *Thermal Comfort*. New York, USA: Mc Graw-Hill, 1970.

[18] *UNI Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort,* UNI EN ISO 7730, 1997.

[19] M. Collares-Pereira and A. Rabl, "The average distribution of solar radiation. Correlations between diffuse and hemispherical and between daily and hourly insolation values". *Solar Energy*, vol. 22, no 2, pp. 155-164, 1979.

[20] R. Lazzarin, *Sistemi solari attivi, manuale di calcolo. (Solar passive systems, a calculation handbook)*. Padova, Italy: F.Muzzio & C, 1981.

[21] A. Carbonari and G. Rossi, "Metodologia per l'ottimizzazione energetica ed illuminotecnica degli elementi ombreggianti applicati alle facciate degli edifici (Methodology for energy and lighting optimization of shading elements applied to building facades)", in *Proc. ATI 1999 - The 54rd Conference,* SGE editoriali Eds. Sep. 1999, pp. 597 - 608

[22] M. Cucumo, D. Kaliakatzos, V. Marinelli and M.D. Vivacqua, "Metodi di calcolo della luminanza del cielo e dell'illuminamento naturale su superfici esterne (Calculation methods of sky luminance and daylighting of external surfaces)", *Condizionamento dell'Aria Riscaldamento Refrigerazione*, vol. 5, pp. 485-496, 1997.

[23] H. M. Traquair,. *An introduction to clinical perimetry*. Edinburgh, UK: sby, 1938.

[24] M. Luckiesh and S. K. Guth, "Brightness in visual field at borderline between comfort and discomfort (BCD)". *Illuminating Engineering*, vol. 44, no. 11, pp. 650 – 670, 1949.

[25] P. Peterbridge and J. Longmore, "Solid Angles Applied to Visual Comfort Problems". *Light and Lighting,* pp. 173 – 177, June 1954.

[26] P. Chauvel, J. B. Collins, R. Dogniaux and J. Longmore, "Glare from Windows: current views of the problem". *Lighting Research & Technology*, vol. 14, no.1, pp. 31-46, Mar. 1982.

[27] *UNI Luce e illuminazione Locali scolastici: criteri generali per l'illuminazione naturale e artificiale*, UNI Standard 10840, 2000.

[28] *CIE Discomfort Glare in interior lighting*. CIE Technical report 117, 1995.

[29] Z. Hamedania, E. Solgia, H. Skatesa, T. Hineb, R. Fernandoa, J. Lyonsa and K. Duprea, "Visual discomfort and glare assessment in office environments: A review of light-induced physiological and perceptual responses". *Building and Environment*, vol. 153, pp. 267-280, Apr. 2019, doi: 10.1016/j.buildenv.2019.02.035

[30] *DIN Innenraumbeleuchtung mit künstlichem licht*. DIN Standard 5035, 1979.

[31] C. L. Robbins, *Daylighting, design and analysis*. New York, USA: Van Nostrand Reinhold Company, 1986.

[32] R. Hopkinson, P. Peterbridge and J. Longmore, *Daylighting*. London, UK: Heinemann, 1963