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ABSTRACT

Although the presence of large window surfaces could be preferable during the heating season when solar gains through the glazed components can overcome heating losses from the same surfaces, during the cooling season more attention has to be paid in order to limit the inlet of solar radiation which causes the increment of cooling load. Generally the optimal tradeoff for energy optimization, as already underlined in a previous paper by the authors, is using low thermal transmittance and high solar factor glazing, even if higher solar transmittance considerably worsens the cooling performance.

However, the choice of glazing type and the design of windows on a façade may depend on comfort consideration besides energetic evaluations. Thermal sensation of an individual is mainly related to the whole thermal balance of the human body. Comfort limits can in this case be expressed by two indexes proposed by Fanger in 1970: the Predicted Mean Vote, PMV, and the correlated Predicted Percentage of Dissatisfied, PPD. The PMV depends on four environmental parameters (air temperature, air humidity, air velocity and mean radiant temperature) and two variables connected with human being (physical activity and clothing). The air temperature, the air humidity and the air velocity inside a building are directly under the system control. In contrast, the mean radiant temperature is strongly conditioned by the envelope surface temperature, and in particular, by the presence of glazed surfaces whose insulating performance is lower than the opaque components one.

In this paper the study of heating and cooling energy needs of an open-space office with different windows' characteristics has been carried out controlling the internal comfort conditions with appropriate setpoint of the system. An office module with windows on a single façade, or on opposite façades, oriented towards 3 different orientations has been simulated, varying the glazed area (2 sizes), the glazing systems (4 types) and considering three localities of central and southern Europe. The PMV have been calculated for each hour of occupation of the whole year assuming two season as regards the setpoint conditions and clothing level. Calculations have then been repeated considering also the effect of the diffuse and beam solar radiation through the windows directly reaching the occupants. The evaluation of the long-term comfort conditions (on seasonal basis) has been conducted considering some statistical indicators of distribution (the median, minimum, maximum and the interquartile range) and the energy performance of the different glazing solution have been compared accounting for the comfort one.

1. INTRODUCTION

The contribution of the windows physical properties to the building energy needs and the simultaneous influence of their characteristics on the thermal sensation of occupants has been studied by many authors from different points of view.

As regards thermal comfort, Hwang and Shu (2011) investigated the effect of different envelope parameters on thermal comfort. Their analysis compared the cooling energy need of a space controlled by a thermostat with a PMV-based control, implementing the approach of Kang *et al*. (2010). According to that concept (Kang *et al*. 2010) the occupants will adjust the room temperature when they perceive uncomfortable indoor thermal environments. Therefore the room temperature should be adjusted with respect to the changes in the indoor climate in order to maintain the same PMV level.

Recently some authors have underlined the importance of taking into account of adaptation possibilities in order to reduce energy needs (Nicol and Humphreys, 2002, Ferrari and Zanotto, 2011), although the European Technical Standard EN 15251:2007 considers this approach only for buildings without mechanical cooling system.

Finally many authors have proposed to correct the classical definition of the PMV to take into account the effect of direct and diffuse solar radiation entering through the glazed areas and directly reaching the people (La Gennusa *et al*., 2005, Singh *et al*., 2008, Hwang and Shu, 2011).

As regards the importance of the glazing system in the optimization of energy need both during the heating and the cooling season, Gasparella *et al*. (2011) underlined the fact that energy optimization does not only depend on the use of insulating glasses, but also on the quantity of solar radiation admitted by the windows. Successively the same authors (Gasparella et al., 2012) analysed the relation between long-term internal thermal comfort, energy performance, kind of glazing and window size, according to the classical definition of the PMV approach.

In this paper different kinds of glazing systems and different windows sizes are compared from energetic point of view, assuming a controlled indoor thermal comfort in an office application. Heating and cooling energy needs have been evaluated through a parametric analysis, considering 96 configurations in three European climates (Rome, Milan and Paris-Trappes). An office module with windows on a single façade, or on opposite façades, oriented towards three different orientations has been simulated, varying the glazed surface entity (2 sizes) and the glazing systems (4 types) and considering three localities of central and southern Europe.

The analysis has been carried out considering two seasons of six months each (winter from 1st October till 31st March and summer from 1st April till 30th September). A control logic acting on the air temperature has been simulated to directly limit the operative temperature within the seasonal ranges prescribed in the Annex A of the EN ISO Standard 7730:2005 for the winter and for the summer season, in consideration of the kind of activity, of the clothing level and for a normal level of expectation (category B).

The PMVs have been calculated for each occupational hour of the whole year. Calculations have then been repeated considering also the effect of the diffuse and beam solar radiation through the windows directly reaching the occupants. The evaluation of the long-term comfort conditions (on a seasonal basis) has been conducted considering some statistical indicators of distribution (the median, minimum, maximum and the interquartile range) and the energy performance of the different glazing solution have been compared accounting for the comfort one.

2. MODEL AND METHOD

A simple three-dimensional office model has been considered and a parametric simulation plan has been developed. The base module is an open office box shaped (Figure 1 a), with a square floor of 100 m^2 and an internal height of 3 m. The roof is horizontal and the floor is considered adiabatic, as could be for the top floor of an office building. The four vertical walls are oriented towards the four cardinal directions.

Both horizontal and vertical walls are composed by a two-layer structure: the internal layer is a clay block of 0.20 m of thickness and the external one is an insulation layer of 0.05 m. The solar absorptance coefficients have been set to 0.6 for the floor (internal side) and 0.3 for the vertical walls and the roof (both sides). The wall emissivity is 0.9, both for the internal and the external side. Different kind of glazings, two double glazings and two triple glazings have been considered (Table 1). A wooden frame with a thermal transmittance of 1.2 W/(m^2 K) and a class-1 edge correlation have been chosen. Changing each parameter among the kind of glazings, the glazing size, the windows distribution and the climatic conditions, 96 configurations to analyze were obtained (Table 1).

Hourly climatic data were calculated from average monthly values from the Italian Standard UNI 10349:1994 for Milan and Rome and from the monthly averages of a TRY weather file (CEC, 1985) for Paris (Trappes) using the TRNSYS subroutine Type 54 Weather Data Generator.

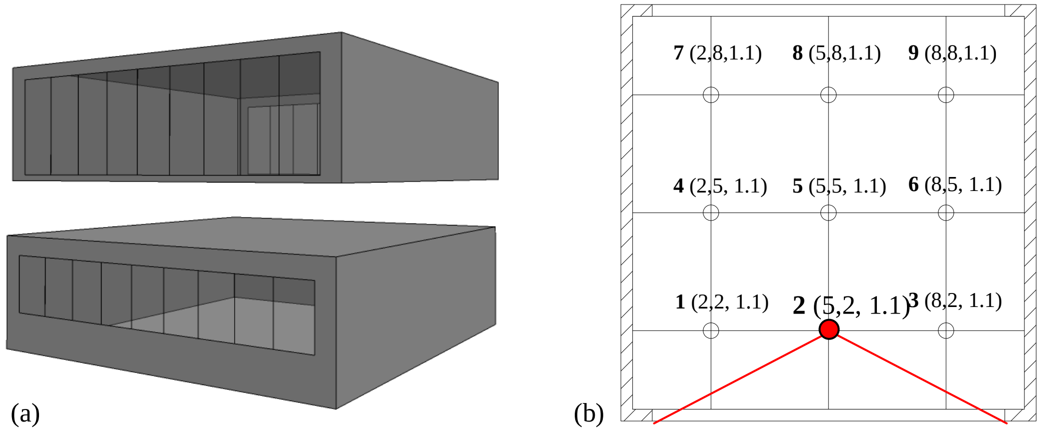

Figure 1: (a) Office module (large size windows (S1) up and small size down (S2))
(b) Coordinates of the positions for the PMV calculations

Table 1: Parameters values varied in the considered configurations and symbols

Parameter	Values
Glazings	Double Glazings (**D**) with high SHGC (**H**):U_{gl}= 1.140 W/(m^2 K); SHGC = 0.608; τ_d = 0.439 Double Glazings (**D**) with low SHGC (**L**): U_{gl}= 1.099 W/(m^2 K); SHGC = 0.352; τ_d = 0.205 Triple Glazings (**T**) with high SHGC (**H**): U_{gl}= 0.613 W/(m^2 K); SHGC = 0.575; τ_d = 0.391 Triple Glazings (**T**) with low SHGC (**L**): U_{gl}= 0.602 W/(m^2 K); SHGC = 0.343; τ_d = 0.191
Windows Size	Size1 (**S1**): width = 9 m; height = 1.5 m; area = 13.5 m^2 (in each façade with windows) Size2 (**S2**): width = 9 m; height = 2.5 m; area = 22.5 m^2 (in each façade with windows)
Windows distribution	East (**E**) East + West (**E+W**) South (**S**) South + North (**S+N**)
Location	Rome: Lat. N 42° 54' 39''/Heating Deg-Days HDD_{18}: 1420 K d/Cooling Deg-Days CDD_{18}: 827 K d Milan: Lat. N 45° 27' 51''; HDD_{18}: 2249 K d – CDD_{18}: 686 K d Paris (Trappes); Latitude N 48° 46' 0''; HDD_{18}: 3015 K d – CDD_{18}: 52 K d

The office occupation period is from 8:00 am to the 6:00 pm, Monday to Friday. Considering an occupancy index of 0.12 people/m^2 the estimated number of occupants is 12. Correspondingly the ventilation rate is set equal to 1.58 ach/h during the occupation time, in accordance to the Italian technical standard UNI 10339:1995, and 0.3 ach/h, as infiltration, for the rest of the time; the indoor air velocity has been fixed in 0.1 m/s. The internal gains, in accordance with the EN ISO 13790:2008, are 20 W/m^2 during the occupation time, and 2 W/m^2 otherwise, a half convective and a half radiant. The vapor flow rate due to occupants have been estimated in 0.05 kg/h per person and the indoor humidity is not controlled by the system.
The whole year has been considered as divided in two main seasons: the winter from 1st October till 31st March and the summer from 1st April till 30th September. The heating and the cooling system have two different set-points depending on the season. The temperature ranges were fixed considering the category B (which should allow a PMV within ±0.5 and a PPD under 10%), as defined in the Annex A of EN ISO 7730:2005, that means for an open office, an operative temperature range from 20 °C to 24 °C for the winter season (clothing index ~1) and from 23 °C to 26 °C for summer season (with clothing index ~0.5). This way the energy needs of the different configurations can be compared for similar internal comfort performance. The system operates from 6:00 a.m. to 6:00 pm during the week-day. During the week-end and the un-occupancy time the heating set-point is 15 °C while there isn't any cooling set-point.
The occupants are assumed with a sedentary activity corresponding to 1.2 met (EN ISO 7730:2005) and a clothing level of 1 clo in winter and of 0.5 clo in summer.
The hourly predicted mean vote PMV_{un} has been calculated according to EN ISO 7730:2005 for 9 positions in the room, as in Figure 1b, each one at 1.1 m from the floor level. However the results are given only for the position 2 due to the limited variability with respect to the position and for the below reasons.

Besides the PMV_{un}, the PMV_{irr} has been calculated only for the position 2 of Figure 1b, which is particularly critical, considering the mean radiant temperature which includes the effect of solar radiation that directly reaches the occupant (La Gennusa *et al*., 2007).
This parameter has been calculated considering a mean radiant temperature calculated as in Equation 1:

$$\overline{T}_{r,irr} = \sqrt[4]{\sum_{i=1}^{N} F_{S\to i} T_i^4 + \frac{C_{dn}}{\varepsilon\sigma}\left(\alpha_{irr,d}\sum_{j=1}^{M} F_{S\to j} I_{d,j}^{in} + C_S^{in}\alpha_{irr,b} f_p I_{bn}^{in}\right)} \quad (1)$$

The diffuse irradiation entering through the windows, $I_d^{\,in}$, has been calculated from the external diffuse irradiation considering the hemispherical transmission coefficients given by WINDOW 6.0 for the four types of glazings (table 1), as in Equation 2:

$$I_d^{\,in} = I_d^{\,out}\,\tau_d \quad (2)$$

Similarly, the beam radiation entering through the glazed surfaces has been calculated considering the external beam radiation on the oriented façade and the hourly optical transmission coefficient of the glazing which depends on the incidence angle, as in Equation 3:

$$I_b^{\,in} = I_b^{\,out}\,\tau_b \quad (3)$$

To calculate τ_b a polynomial function was extrapolated from the optical characteristics given by WINDOW 6.0 for a step of 10° of the incidence angles. The expression used is reported in equation 4 and the coefficients τ_j for the calculation are reported in Table 2:

$$\tau_b = \sum_{j=0}^{5} \tau_j \cos^j \theta \quad (4)$$

The beam solar radiation reaching the considered point has been determined considering the position of the sun with an hourly time step and comparing the azimuth and the altitude angle with the maximum angles for the geometry of the windows.
The calculation of energy needs were performed in TRNSYS 17.0 which enables 3D modeling of the ambient radiation exchanges. The determination of the hourly variables for the calculation of the PMV_{un} and PMV_{irr} was implemented in a specific spreadsheet.

Table 2: Coefficient for the calculation of the optical transmittance of the glazed surface as function of the index j in Equation 4.

Glazings \ *j*	**0**	**1**	**2**	**3**	**4**	**5**
DH	0.000065	0.704394	1.81754	-4.42961	3.0049	-0.58308
DL	0.000089	0.147051	1.416712	-2.76692	1.87247	-0.41109
TH	0.000116	0.261403	2.465889	-3.7646	1.232372	0.283623
TL	0.000143	-0.011	1.270238	-1.16944	-0.348993	0.518541

3. RESULTS

The simulations results have been represented in terms of PMV_{un} (Figures 2 and 3, for winter and summer respectively) and PMV_{irr} (Figure 4) distribution, both only for the position number 2, indicating minimum and maximum, the median and the interquartile range IQR for each configuration, and referring only to the occupancy period. With this representation the distribution of the values is particularly evidenced as each individuated range comprises 25% of the occurrences. Due to the control strategy the conventional PMV_{un} should result in the range of the comfort category B (±0.5) as would be required to compare the heating and cooling energy needs (represented in the same Figures 2 and 3) of the different configurations under equivalent (if not the same) comfort conditions. Even if this is not completely verified, for a given locality the PMV_{un} lays in an almost constant range allowing this evaluation at least location by location. In the next two sections the results will be discussed starting from the winter season and moving to the summer season.

3.1 Rome, Milan and Paris - Winter

As regards Rome, the mean values and the dispersion of the PMV_{un} values change when the windows size (Figure 1), the windows orientation and the solar heat gain coefficient of the glasses change. Anyhow, the PMV_{un} vary from the minimum of –0.6 to the maximum of 0.8 in all cases, and the IQRs generally are always between ±0.5. The wider and higher IQRs are given for the larger windows area and in East+West, South and South+North orientations. Comparing the glazing systems, it is noticeable that negligible differences appear for the PMV_{un}

distribution of glazings with the same Solar Heat Gain Coefficient (SHGC). Moreover the high SHGC reduces the differences in the distribution of PMV_{un} with respect to the increase of the windows size. This is true for all the orientation except for the East one.
Moving to the energy needs analysis, for a given kind of glazing, the larger size S2 of the windows reduces the heating energy needs in all the orientations except for the East one, where enhanced solar gains are balanced by enhanced dispersion. Adding windows on the opposite side of the room, when the increased area is North exposed, increases the heating energy needs for all the glazing systems except for triple glazing and for wider size windows S2: in that case the energy need is the same as with window only on the south façade. Comparing the glazing systems the most convenient way to reduce heating needs is to adopt the triple glazing with high SHGC for all the situations. However the double glazing with high SHGC gives similar energy needs. Winter cooling needs become significant when increasing the window area only for the orientation East+West, South and South+North, but only for the high SHGC solutions.
However, when the solar radiation entering through the windows and hitting a person is accounted, the higher SHGC values present some drawbacks. Looking to the PMV_{irr} distributions (Figure 4), the glazing systems with high SHGC presents the highest maximum values (about 1.4 for East and East+West orientation, and well above the full scale value of 3 for South and South+North orientation) determining, even if temporarily, very bad thermal indoor conditions. Except for this extreme condition the mean value is still in the comfort category B which, according to the ISO 7730:2005, includes PMV values between the range ±0.5. Nevertheless the third quartile overcome the upper limit of +0.5.
Also in Milan, the PMV_{un} distributions (Figure 1) range between –0.6 and 0.8, but with narrower IQRs and mean values much more aligned than in Rome. In all the cases the 50% of the PMV_{un} values are under the zero and between –0.3 and –0.4, that means that the thermal sensation is a little cooler than the neutrality.
For each type of glazing increasing the size of the windows generally reduces the heating energy needs, except for the East orientation and double glazing with high SHGC and for the South orientation and double glazing with high SHGC. Adding windows on the opposite side is ineffective or slightly penalizing when the increased area is North exposed otherwise it has positive effect in energy saving. For the same type of glazing, the orientation and size combination which leads to the lower heating need is the South with the larger size of window S2. Comparing the glazing systems, the most convenient to reduce heating needs is again the triple glazing with high SHGC for all the situations. The double glazing with high SHGC gives similar needs only for east orientation. Winter cooling needs are almost null for low SHGC glazings and are between 1 and 2 GJ in the other cases.
When considering the solar radiation through the windows hitting the person (Figure 4), the maximum PMV_{irr} values overcome the value of 0.7 (which is the upper limit for the comfort category C of EN ISO 7730:2005) in all cases, and for the high SHGC glazing they largely overpasses the full scale 3 for South and South+North orientation. Nevertheless as it happens for Rome climate, the IQRs never overcome +0.5.
In the climate of Paris the PMV_{un} distributions (Figure 2) show minimum and the maximum ranging from –0.6 to 0.6 for all the orientation except for the East one, for which minimum is 0 (smaller windows) or 0.1 (larger windows). The IQRs are very narrow (between 0.3 and 0.4) for all cases and the mean values are aligned to –0.4. Even in this case, as for Milan, the generally thermal sensation is slightly cooler than the neutrality.
Increasing the size of the windows for each type of glazing does not affect so much the heating energy needs and in some cases it slightly increases the heating need. As for Milan and for Rome, adding windows on the opposite side is ineffective or slightly penalizing when the increased area is north exposed otherwise it has positive effect in energy saving. For the same type of glazing, the orientation and the size combination which lead to the lower heating need is South and larger size (S2). Comparing the glazing systems the most convenient to reduce heating needs is still the triple glazing with high SHGC for all the situations. Winter cooling needs are almost always null.
The interquartile ranges the distributions of PMV_{irr} (Figure 4) are very narrow as for the PMV_{un} with the only exceptions for the South and South+North orientations and for double high and triple high SHGC glazings where the IRQ amplitude swings from 0.5 to 0.8. In general, the presence of solar radiation hitting the person seems to improve in average the thermal sensation, but could leads to some extreme situations of discomfort as it happens for Rome and Milan for double and triple glazing with high SHGC and for South and South+North orientation.

3.2 Rome, Milan and Paris - Summer

In the climate of Rome, the PMV_{un} ranges between –0.8 and 0.6 in almost all the cases (Figure 3). The mean values swing from 0.2 (just few cases) to 0.4. The IQRs are narrower than in the winter case and between 0 and 0.4, widely in the range of the thermal comfort category B. The wider IQRs are for the glazings with low SHGC.
Almost no heating needs are present in summer. Concerning the cooling needs, for each type of glazing and for each orientation, increasing the size of the windows strongly increases the cooling energy needs. For the same glazing

type and for the same window size, the largest cooling needs are found for orientation South if windows are present only on one façade and for the East-West orientation when windows are present on the opposite façades. It is noticeable that in the first case the difference in cooling needs from South and East orientation are not so relevant, while the cooling needs is greatly higher for East+West orientation than for the South+North especially for high SHGC. Comparing the different glazing types, the double and the triple with low SHGC give the lowest cooling needs and their values are very similar. The SHGC appears to be the only relevant parameter in this climate, in which the thermal losses have modest impact on the building heat balance, and this consideration is in accordance with the findings of some previous works (Gasparella *et al*. 2012).

The presence of the solar radiation entering through the windows generally doesn't affect the mean value of the PMV nor the third quartile value (Figure 4). For the double and triple glazings with high SHGC the maximum values of PMV_{irr} reaches values of about 1.1 for South and South+North orientation, but reaches the value of about 2 for East and East+West orientation. For the other two types of glazing the maximum values are reached for the East and the East+West orientation but it doesn't overcome the value of 1.2.

As regards Milan, the PMV_{un} values ranges between –0.8 and 0.6 in almost all the cases; the only exceptions are for low SHGC glazings and East orientation for which the maximum PMV_{un} values is 0.7. The mean PMV_{un} value is about 0.3 and the IQRs are wider than for Rome especially for the low SHGC glazings, but don't overcome the amplitude of 0.4.

Almost no heating needs are present. Again increasing the size of the windows strongly increases the cooling energy needs. The cooling needs for orientation East do not prevail over the South orientation, as it occurs in Rome but still have the most important sensitivity to the addition of windows on the opposite side (East+West) and still this last orientation gives the greatest level of cooling need for all the type of glazings.

As regards the type of glazing, the differences between double and triple glazings with similar SHGCs are negligible, either considering the energy needs or the PMV_{un} values. Glazings with low SHGC give the lowest cooling needs when given the other conditions.

Considering the PMV_{irr} the considerations are quite similar to the ones for Rome. The solar irradiation increases slightly the median of about 0.1 but just for some orientation. Maximum values increases very much for glazing with high SHGC especially for East and East+West orientation approaching the value of 2. The interquartile ranges have negligible differences from the unirradiated cases. For the glazings with low SHGC the maximum values of PMV_{irr} is about 1 for East and East+West orientation and of 0.8 for other orientation. However, the IQR for the PMV_{irr} is always inside the interval of the B category of indoor environment (±0.5).

Finally as regards Paris, the PMV_{un} ranges, similarly to the other localities, from the minimum value of -0.8 to the maximum value of 0.6. The mean value has a discrete variability for the same glazing type increasing when the window size increases and, for high SHGC glazing, it reaches the values of 0 for the larger size of window for orientation East+West, South and North+South. The distribution of PMV_{irr} is similar to the one of PMV_{un} except for the maximum values as it happens for Rome and Milan.

Heating needs prevail over cooling needs in all the cases when the glazing has low SHGC and in some cases, such as for east and south orientation in other cases. Considering the cooling needs again increasing the size of the windows strongly increases the cooling energy needs. East+West orientation gives the greatest level of cooling need for all the type of glazings. As in Milan and in Rome also in Paris the cooling needs are driven by the SHGC coefficient and the differences between the double and the triple glazing with the same SHGC are negligible.

Maximum PMV_{irr} swings from 1 to 2 for high SHGC glazings, depending on the orientation and the size of the window: this behavior is quite different from the other localities. For the low SHGC glazings the maximum values are quite constant at 0.6 for East and East+West orientation and they vary from 0.7 to 0.9 for the other orientations. Also in this climate the IQR is kept inside the thermal comfort range of ±0.5.

4. CONCLUSIONS

In the present paper the energy performance of different kinds of glazing systems have been evaluated for given comfort conditions, in order to identify the importance of the thermal transmittance and of the SHGC in relation to different orientations, window size and envelope insulation for three European climatic conditions. The results confirmed that for equivalent interquartile distribution of the PMV_{un} there is a strong influence of the SHGC also on the winter energy needs, as already found in some previous works. In particular double glazings with high SHGC tend to have at least as good winter performance as triple with low SHGC. Low SHGC double or triple glazings are preferable in summer in particular for East orientation.

Concerning the comfort conditions, the SHGC again is the controlling parameter, in particular in winter, when evaluating the effect on the PMV_{un} distribution. Low SHGC leads to narrower IQRs in winter with small and different effects in summer. However, when the solar radiation hitting the occupant is considered, PMV_{irr} maximum value with high SHGC are dramatically increased in particular for South and South+North orientation in winter and for the Southern climates. Minor effects are seen for East and East+West orientation in summer. In conclusion high SHGC triple glazings appear to be slightly preferable to double glazings in Rome, Milan and Paris, providing suitable moveable shading devices especially for the South orientations for winter comfort and for the East and East+West for summer energy performance.

NOMENCLATURE

$\overline{T}_{r,irr}$	Mean radiant temperature including entering solar radiation	(K)
T_i	Temperature of surface i	(K)
$F_{S\rightarrow i,j}$	Angle factor between the window and the person	(-)
C_{dn}	Day-night coefficient	(-)
I_d^{in}	Intensity of the inner diffuse solar radiation	(W m^{-2})
I_{bn}^{in}	Intensity of the indoor beam solar radiation on a surface orthogonal to solar ray direction	(W m^{-2})
I_b^{out}	Intensity of the external beam solar radiation	(W m^{-2})
I_d^{out}	Intensity of the external diffuse solar radiation	(W m^{-2})
C_S^{in}	Inner building shading coefficient	(-)
HDD_{18}	Heating degree days with respect to an internal reference temperature of 18 °C	(K d)
CDD_{18}	Cooling degree days with respect to an internal reference temperature of 18 °C	(K d)
SHGC	Solar heat gain coefficient	(-)
U_{gl}	Glazing thermal transmittance	(W m^{-2} K^{-1})
Greek Symbols		
$\alpha_{d,\,b}$	Absorption coefficient of the subject referring to the diffuse or beam solar radiation	(-)
ε	Emissivity of the subject	(-)
θ	Angle between the direction of the solar rays and the normal to the glass	(°)
σ	Stephan- Boltzmann constant (5.67 10^{-8})	(W $m^{-2}K^{-4}$)
$\tau_{d,\,b}$	Optical transmittance of the glass for the diffuse or the beam component	(-)

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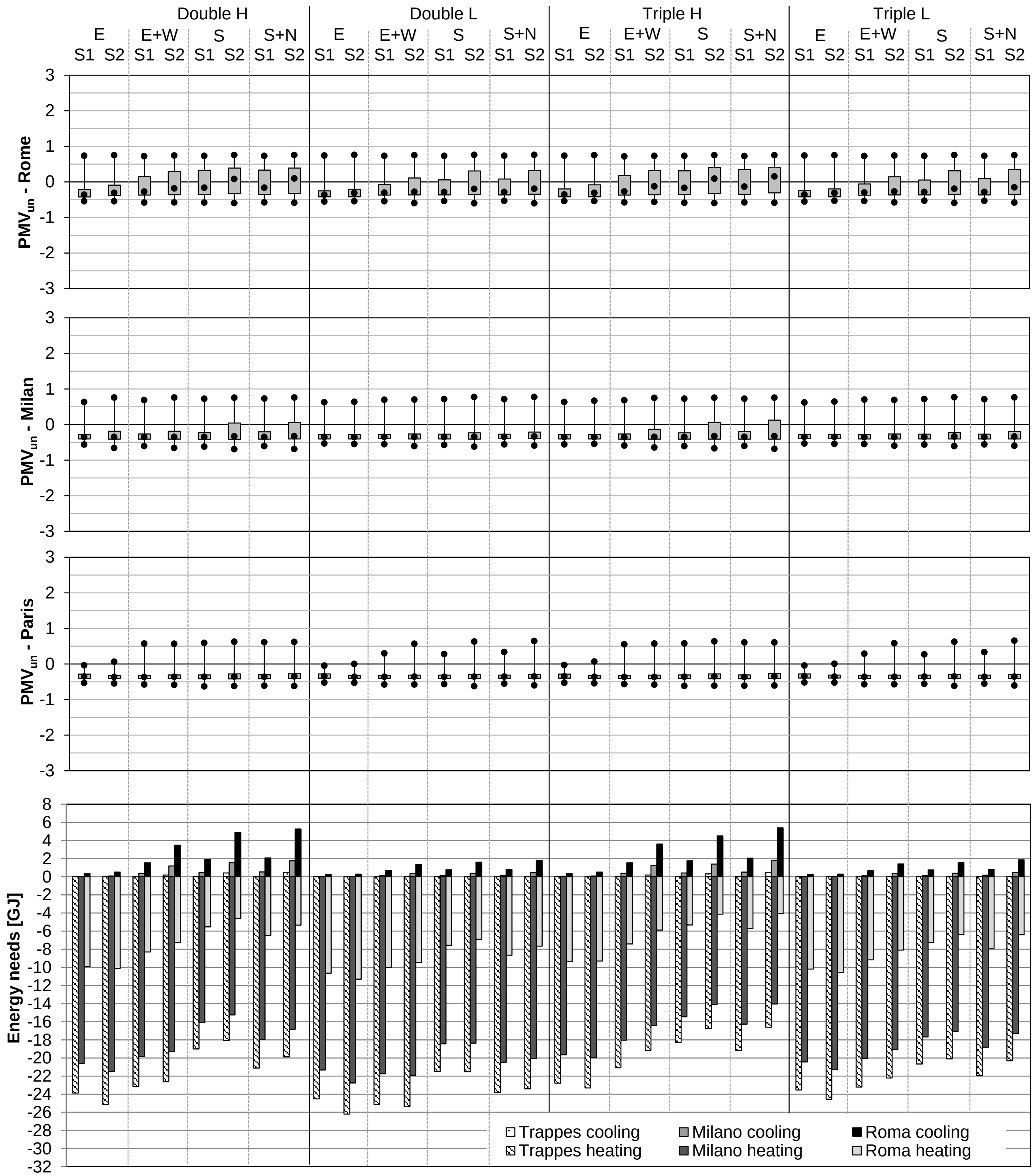

Figure 2: Rome, Milan and Paris – Winter PMV_{un} distributions (the upper dot represents the maximum, the intermediate the median, the under dot the minimum and the box the interquartile range) and winter Energy Needs.

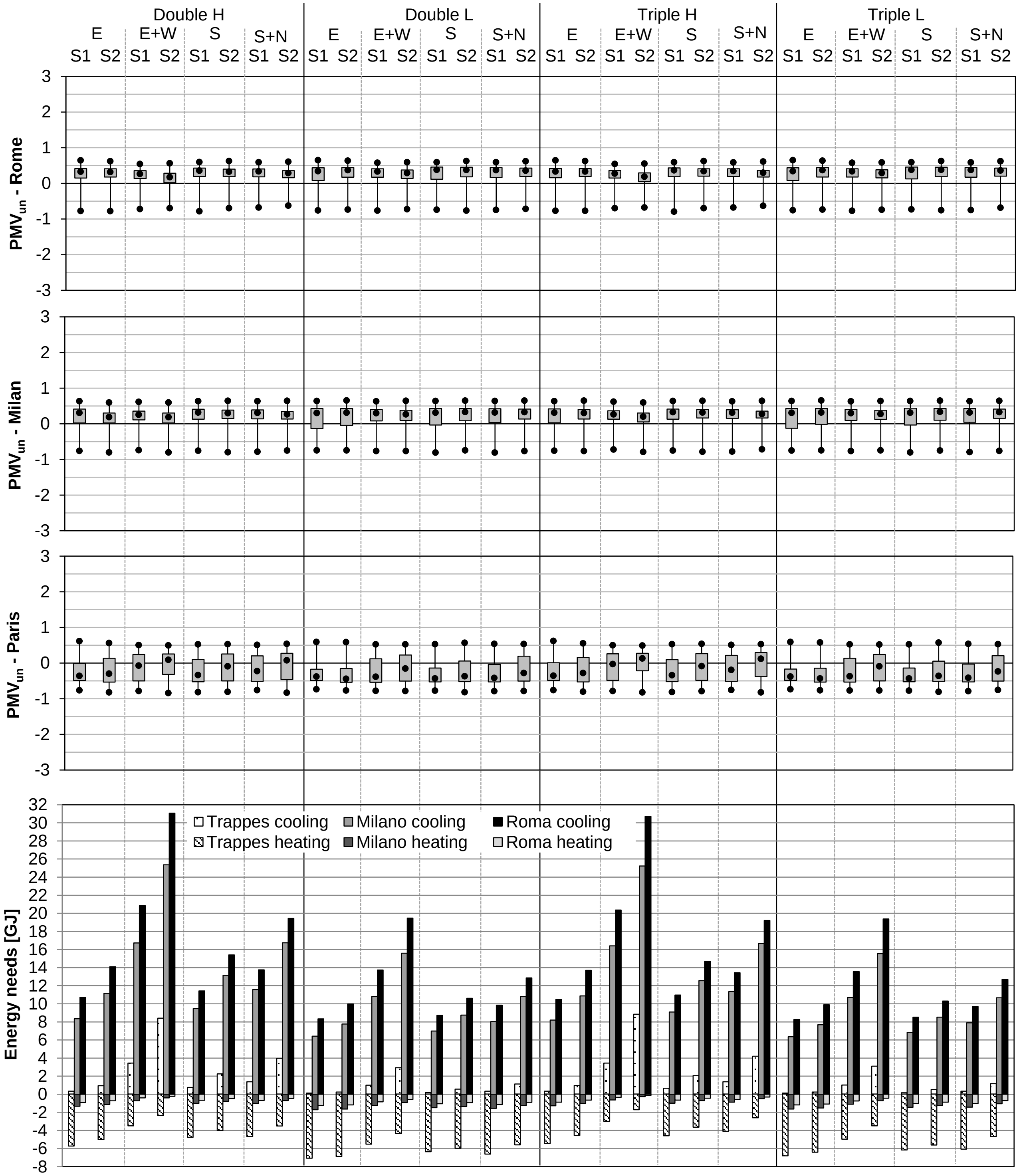

Figure 3: Rome, Milan and Paris – Summer PMV_{un} distributions (the upper dot represents the maximum, the intermediate the median, the under dot the minimum and the box the interquartile range) and summer Energy Needs.

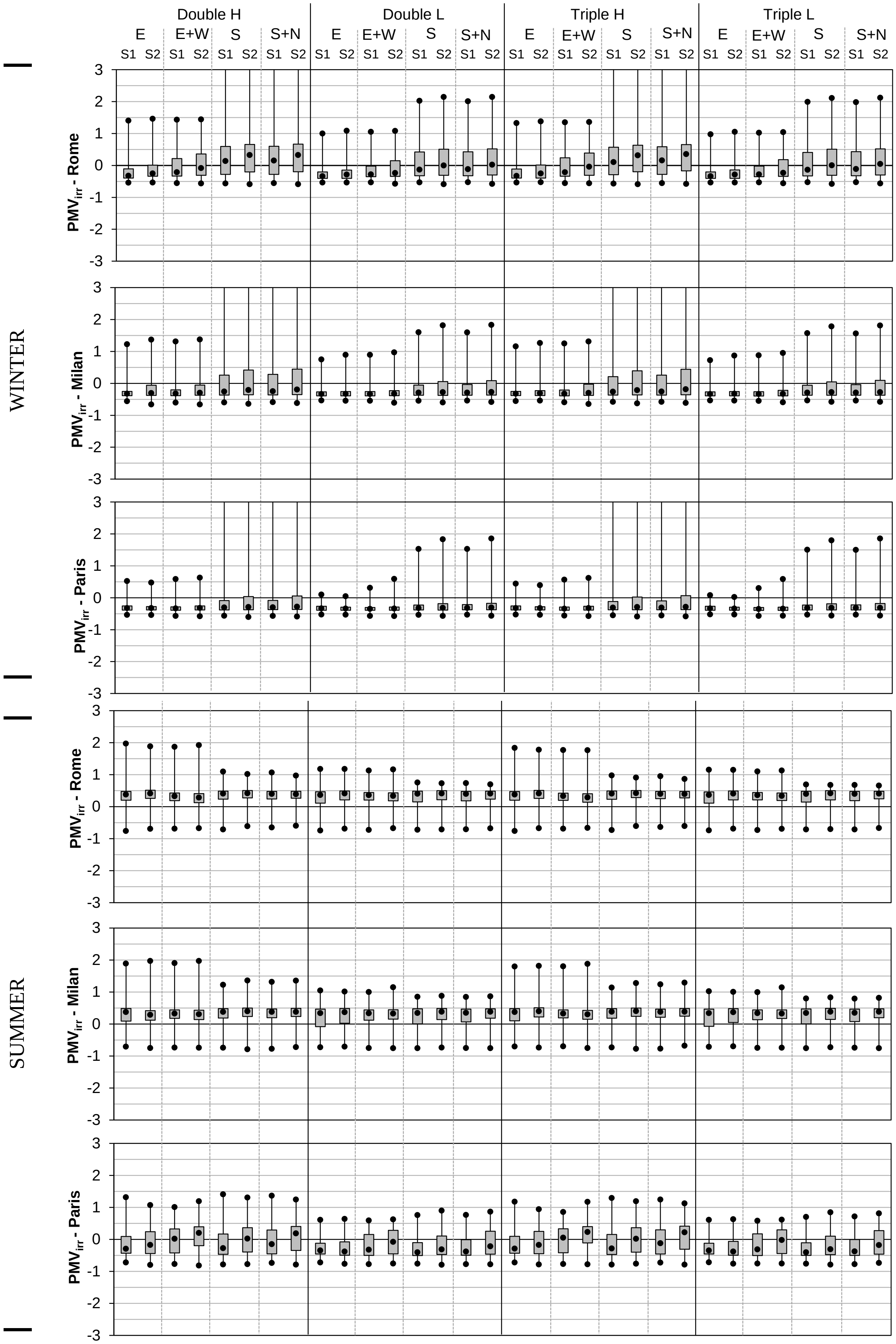

Figure 4: Rome, Milan and Paris – Winter (above) and Summer (under) PMV with solar irradiation statistical distributions.