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Internal versus external shading devices performance in office buildings

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Abstract

In this paper different configurations of an open-space office located in Rome has been simulated with EnergyPlus 8 to compare the performance of outdoor and indoor shading devices concerning the thermal and visual comfort and the overall primary energy use. The standard PMV indices [1] have been calculated considering also the effect of the diffuse and beam solar radiation directly reaching the occupants through the windows. Although the use of shades always improves the thermal comfort, the energy demand could increase as an effect of the internal position of shades in combination with particular orientations and glazing types.

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Keywords: *shading device; windows performance; energy demand; thermal comfort; Predicted Mean Vote*

1. Introduction

The most recent buildings are often characterized by an extensive use of glazing façades. The presence of large transparent components and the application of shading devices have been usually object of analysis because of the large influence of solar gains on the building thermal energy performance, in both summer and winter seasons, on the lighting energy demand and on thermal and visual comfort. In the scientific literature about solar radiation management these are some of the most relevant topics currently treated by the researchers. Moreover, office

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buildings, which are characterized by a special energy demand for lighting and cooling and by particular thermal and visual comfort requirements, represent the preferred research application field.

In general, all the literature on solar shading devices is oriented to the evaluation of the strategies for the daylight harvesting in order to reduce lighting consumption, for the cooling or heating energy saving and for the indoor thermal and visual comfort, but only a few authors analyze all these aspects together.

As regards energy aspects, some authors have compared the influence of different kinds of glazing and shades on the heating and cooling energy needs in office buildings with a parametrical approach in order to evaluate different building configurations [2, 3, 4, 5]. Tsikaloudaki et al. [6] carried out a similar analysis on a residential building and proposed some correlations to calculate the cooling energy contribution of windows on the basis of their thermal and solar transmittance. The relation between the use of shading devices and availability of natural light was investigated by Kim et al. [7] who suggested that optimal shading systems should increase daylight levels while controlling the amount of excessive sunlight. Tzempelikos and Athienitis [8] optimized the selection of the window size and of the properties of shades with reference to the overall energy performance considering different control strategies.

Some other studies focused on the assessment of both thermal and lighting energy performance and thermal and visual comfort performance for different shading devices [9, 10]. David et al. [10] evaluated the relations between some simplified performance indicators of energy demand, thermal comfort and visual comfort, i.e. the solar shading coefficient, cooling energy demand, daylight autonomy and sun patch index on work plane. Tzempelikos et al. [11] introduced a transient thermal comfort model to investigate singularly the impact of different shades and three kinds of glazing on mean radiant and operative temperatures, thermal discomfort index, radiant asymmetry, and daily heating needs for a perimeter office with a high window area. The combined effect of different shading devices and shading control strategies for visual comfort optimization and for artificial lighting minimization has been analyzed by some authors [12, 13, 14]. Shen and Tzempelikos [15] studied the tradeoffs between daylighting and control of solar gains in perimeter private offices with automated interior roller shades, taking into account glazing and shading properties and control together with window size, climate and orientation integrating daylighting and thermal analysis.

Thermal comfort aspects have been included in terms of calculation constraints by Nielsen et al. [16] who calculated the energy demand and the daylight level of a single office comparing different situations of shading, imposing an internal setpoint for heating/cooling and air flow rates for mechanical ventilation required for comfort class II in the Standard EN ISO 15251:2007 [17]. Also Poirazis et al. [18] used a comfort setpoint strategy for operative temperature and illuminance. A minimum acceptability level for thermal comfort satisfaction was introduced.

In this paper, the energy performance of three roller shades combined with different glazing systems and on the outside and inside of windows has been evaluated calculating their effect on the total energy needs of an office module, fixing the indoor thermal and visual comfort conditions. The thermal comfort has been controlled by an operative temperature setpoint consistent with the comfort conditions of class II of EN ISO 15251:2007. The visual comfort requirements has been taken into account by fixing a maximum limit value for the glare index and a minimum illuminance level to be meet through respectively the shading system control and artificial lighting integration.

Simulations have been performed in Rome climatic conditions [19] considering different building configurations. Windows on a single façade, or on two opposite façades, have been simulated, varying the glazed area (2 sizes) and the glazing systems (4 types). The PMV indices have been calculated for each hour of occupation of the whole year in 9 positions, assuming two seasons with regard to the set point conditions and clothing level. Calculations took also into account the effect of the diffuse and beam solar radiation through the windows directly reaching the occupants in two of the above positions. The evaluation of the long-term thermal comfort conditions has been conducted by means of some statistical indicators of distribution (median, minimum, maximum and interquartile range) and the energy performance of the different shading solution has been compared accounting for comfort as well. Energetic, comfort and lighting simulations have been carried out with Energy Plus 8, while the correction on the PMV for the solar radiation has been elaborated using a spreadsheet.

2. Simulation assumption

The model is an open space office of 100 m^2 of floor area and 3 m of interior height. Vertical walls and roof are

Nomenclature

HDD_{18}	Heating Degree Days with reference temperature 18 °C
CDD_{18}	Cooling Degree Days with reference temperature 18 °C
$F_{S\rightarrow i,i}$	Angle factor between the window and the person (-)
f_p	Projected area factor of the subject in the solar beam direction (-)
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})
PMV	Standard Predicted Mean Vote according to EN ISO 7730:2005 definition (-)
PMV_{irr}	Predicted Mean Vote in presence of solar irradiation directly hitting the occupant (-)
$SHGC$	Solar Heat Gain Coefficient (-)
T_i	Temperature of surface i (K)
MRT	Mean radiant temperature (K)
MRT_{irr}	Mean Radiant Temperature including entering solar radiation (K)
OT	Operative Temperature (K)
U_{gl}	Glazing thermal transmittance (W m^{-2} K^{-1})
$\alpha_{irr,\, d/b}$	Absorption coefficient of the subject referring to the diffuse or beam solar radiation (-)
ε	Emissivity of the subject (-)
σ	Stephan- Boltzmann constant (5.67 10^{-8})(W $m^{-2}K^{-4}$)
$\tau_{d/b}$	Transmittance of the glass for the diffuse or the beam component of solar radiation (-)
$\tau_{s/v}$	Shades solar and visible transmittance (-)
$\rho_{s/v}$	Shades solar and visible reflectance (-)

all external while the floor is modelled as adiabatic. The composition of all the opaque elements, both vertical walls and roof slab, is identical, with a 20 cm thick internal layer of clay block and a 5 cm thick external insulation layer. The structure has a thermal transmittance of 0.45 W m^{-2} K^{-1}. The solar absorptance is 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. The light reflection coefficients have been set to 0.4 for the floor (internal side) and 0.7 for the vertical surfaces (both side) and for the ceiling.

A parametrical analysis has been performed by varying the building envelope parameters summarized in Table 1, and in particular considering three different types of roller shades in two position (inside and outside of the windows).

The office is occupied from 8:00 am to 6:00 P.M., Monday to Friday. The occupancy index has been fixed as 0.12 people m^{-2} [20].

The occupants' metabolic heat flux is equal to 70 W m^{-2} or 1.2 met. The heat flow is divided into the sensible portion of 75 W (58% as radiant exchange) and latent heat of 55 W. The clothing unit thermal resistance is 1 clo during the winter season (from 1st October to 31st March), and 0.5 clo during the summer (from 1st April to 30th September). People are sitting at their desk with the side towards the windowed wall.

The internal loads related to electrical equipment are quantified considering 12 personal computers, 12 monitors, a laser printer and a copier, with constant average power during the occupation period.

The considered Light Power Density (LPD) is 12 W m^{-2}, with fluorescent lamps installed on the ceiling. During occupation period, artificial lights are dimmered depending on the level of natural illumination, in order to maintain 500 lux of illuminance level [21]. The shading devices are closed when the external total radiation on the window surface overcomes 150 W m^{-2}. This setpoint value has been chosen considering that people don't usually shut the shades when solar radiation is below 50-60 W m^{-2} while normally they need to close them above 250–300 W m^{-2} ([22] [23] [24]). A second control criterion is based on a Daylight Glare Index (DGI) limit value of 22 for the position 5 (Fig. 1), which corresponds to a value of Unified Glare Rating (UGR) of 19, as required by [17] to ensure the comfort of light inside the confined spaces for office use.

Table 1. Variables set for the analysis

FACTOR	VALUES	FACTOR	VALUES
Location	Rome: Lat. N 42° 54' 39'' Heating Degree-Days HDD_{18}: 1420 K d Cooling Degree-Days CDD_{18}: 827 K d	Window Size	S1: width = 9; height = 1.5 m; area = 13.5 m^2 S2: width = 9; height = 2.5 m; area = 22.5 m^2
Glazing	DH: Double Glazing with high SHGC U_{gl} = 1.140 W m^{-2} K^{-1}; $SHGC$ = 0.608; τ_d = 0.439 DL: Double Glazing with low SHGC U_{gl} = 1.099 W m^{-2} K^{-1}; $SHGC$ = 0.352; τ_d = 0.205 TH: Triple Glazing with high SHGC U_{gl} = 0.613 W m^{-2} K^{-1}; $SHGC$ = 0.575; τ_d = 0.391 TL: Triple Glazing with low SHGC U_{gl} = 0.602 W m^{-2} K^{-1}; $SHGC$ = 0.343; τ_d = 0.191	Window distribution Shadings	S: South S+N: South + North E: East E+W: East + West W/O: Without shades: SH1: High solar transmittance roller shades: ρ_s = 0.58; τ_s = 0.16; ρ_v= 0.51; τ_v = 0.15 SH2: Medium solar transmittance roller shades: ρ_s = 0.37; τ_s = 0.10; ρ_v= 0.35; τ_v = 0.10 SH3: Low solar transmittance roller shades ρ_s = 0.13; τ_s = 0.05; ρ_v= 0.06; τ_v = 0.05

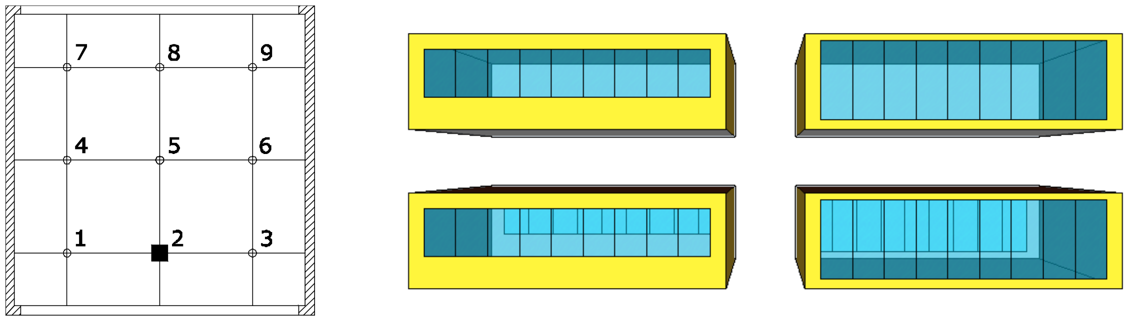

Fig. 1. plan of the office model and occupants' positions for the PMV calculations and 3D-models of the different cases simulated.

The heating and cooling system is controlled considering two bands for the operative temperature, 20 °C to 24 °C for winter and 23 °C to 26 °C for summer, just during weekdays, to comply with the comfort Category II [17] (normal level of expectation about the conditions of comfort for users). Heating setpoint of 15 °C and cooling of 38 °C has been considered for the nighttime and weekends. To assess the comfort conditions inside the office, a grid consisting of 9 points, each one at 0.8 m from the floor level was considered.

The comfort conditions have been evaluated only during the occupancy period. Besides the standard PMV, the PMV corrected (PMV_{irr}) considering the mean radiant temperature which includes the effect of solar radiation that directly reaches the occupant [25, 26], has been calculated for the positions 5 (the setpoint control position) and 2. The latter is considered a particularly critical point next to the E or the S windows.

For this aim, a new mean radiant temperature (MRT_{irr}) was determined adding to the standard MRT the contributions of diffuse and the beam solar radiation entering through the windows and reaching the occupant:

$$MRT_{irr}^{\ 4} = \sum_{i=1}^{N} F_{S\to i} T_i^4 + \frac{\alpha_{irr,d}}{\varepsilon\sigma} \sum_{j=1}^{M} F_{S\to j} I_{d,j}^{in} + \frac{\alpha_{irr,b}}{\varepsilon\sigma} f_p I_{bn}^{in} \qquad (1)$$

EnergyPlus enables both energy and daylighting simulation of complex glazing and moveable shading systems. Detailed evaluation of the system optical properties and heat balance considering the contribution of each layer is considered for the thermal balance. Daylight and glare analysis is performed through the calculation of proper hour daylight factors (daylight coefficients method) for the reference sky types which are then interpolated and used with the actual outside conditions.

3. Results and discussion

3.1 Indoor thermal comfort

Concerning the smaller windows S1, the distributions of the PMV_{irr} during the winter season have been plotted for internal and external shades respectively in Fig. 2a and 2b, while Fig. 2c and 2d refer to the summer. Just point 2 is analyzed. The upper lines represent the maximum values, the lower lines the minimum, the points in the middle the medians and the rectangular boxes the range between the first quartile and the third quartile.

As regards the winter season, comparing internal and external shadings it can be seen that the maximum, the minimum and the first quartile values are very similar thanks to the temperature control strategy. Only the median values and the third quartile values are affected by the shade position. In particular the difference is very small for E orientation and it increases for the other orientations. The difference in the median is also influenced by the glazing type: high SHGC glazing leads to warmer sensation (above the PMV_{irr} 0.5) with internal shades and neutral sensation with external shades. PMV_{irr} values generally increase when the internal shade solar transmittance decreases, while opposite happens for external shades, particularly for orientations E+W and S+N. With external shades the 75% of the occupancy hours lay inside the comfort category B while with internal shades especially for high SHGC glazing and S or S+N orientation the percentage is lower than the 75%.

In summer (Fig. 2c and 2d) PMV_{irr} values have a smaller dispersion than during the winter season, with the application of the shades that further reduces the variability of the comfort index. The lower the transmittance, the narrower is the PMV_{irr} distribution. Some peaks in maximum values are produced by solar radiation but just for windows without shades or with the high solar transmittance shades SH1 and just for high SHGC glazing in all the orientations.

The thermal sensation does not appear to be affected by the position of the shade, probably because in summer the inlet of beam solar radiation through the window is rare. That is confirmed also by the maximum values reached during this season if compared to the winter maxima. Finally, both with external and internal shades the 95% of the PMV_{irr} values lay inside the comfort category B.

As for the largest windows (Fig. 3a to 3d), similar considerations hold. However, higher maximum values for unshaded windows are shown in winter for all the orientations both for double and triple glazing with high SHGC. The interquartile ranges are wider than for the smaller windows but the comparison between the two positions of the shades leads to the same considerations. In general all the external shades with lower transmittance (SH2 or SH3) when controlled for visual comfort allow maintaining the PMV_{irr} within an acceptable range.

3.2 Indoor visual comfort

The annual number of occupied hours for which the DGI exceeds the limit value of 22 have been calculated. For reference, annually the hours of occupation are 2500.

The glare evaluation for configurations without shading devices for the S or S+N orientations, indicates more than 600 discomfort hours per year with small windows, whatever is the kind of glazing. This means that the occupants in position 2 will fall under conditions of visual stress for about 30% of their working time. The use of roller shades makes null the hours of discomfort no matter if they are internal or external.

3.3 Heating, cooling and lighting energy use

Heating, cooling and lighting energy performance have been evaluated in terms of primary energy use for small and large windows (Fig. 4) in order to allow the comparison through a single global indicator. Conventional values of 0.8 as seasonal thermal energy production efficiency, 3 as seasonal Energy Efficiency Ratio for cooling and 2.174 primary energy content per unit of electrical energy were assumed.

Considering the cases without shadings, for both sizes S1 and S2, TL glazing systems are the best performing for any orientation, with DL not too far. Triple are always better than double for the same SHGC. Low SHGC are better than high, with differences emphasized by double orientations especially for E+W. In particular, with size S2 E+W cases have worse performance than N+S and E worse than S.

The introduction of shades can affect very differently the energy performance of the office, depending on their position, the type of shades, the orientation of the windows and the windows size. Some general trends can be drown. Shading systems increase lighting needs both for external and internal position. However, while for the external position cooling needs are reduced and heating are slightly increased, internal shades gives a strong increase of cooling needs that is not compensated by a corresponding reduction of the heating ones. Therefore, external systems always perform better than internal ones.

Considering just the cases with shades, it can be observed that the lower is the shading solar transmittance, the higher is the primary energy needs, both for external and internal position. This increase is mainly due to the rising lighting needs for external shades, while higher cooling needs also contributes when shades are positioned inside. The reduction of heating needs provided by internal shading systems is almost insensitive and slightly sensitive to the solar transmittance for window size S1 and S2, respectively. This means that SH1 shades are always preferable to the SH2 and SH3. Only exceptions to the above considerations are those with the external shades, E+W orientation and high SHGC glazing, when low solar transmittance shades have non-worse or even better performance than higher solar transmittance elements for small and large size windows, respectively.

With respect to unshaded cases, the introduction of shading system is seldom beneficial when combining low solar transmittance shades with low SHGC glazing systems, S or even E orientations and smaller size windows. In particular (Table 2) there are no improvements with:

- windows size S1, external position and orientation:
  - E for DL, TL and for DH and TH glazing with SH3 shades
  - S for any kind of shades
  - S+N again for DL and TL glazing systems
- windows size S1, internal position and orientation:
  - E for glazing DL, TL, TH and for DH with SH2 and SH3 shades
  - E+W for shades SH3 and also for shades SH2 with DL and TL
  - S for any kind of shades
  - S+N for glazing DL, TL, and DH with SH2 or TH with SH2 and SH3
- windows size S2, external position and orientation:
  - E for glazing DL and TL with SH3 shades
  - S for DL and TL glazing and for TH with SH3 shades
- windows size S2, internal position and orientation:
  - E for DL, TL and for DH and TH glazing with SH3 shades
  - E+W and S+N for SH3 shades and S+N also for TL glazing and SH2 shades
  - S for DL, TL and DH with SH2 or TH with SH2 and SH3

Table 2. Improvement (1) or worsening (0) in primary energy needs provided by shading systems with respect to unshaded cases.

Orientation	E											
Glazing	DH			DL			TH			TL		
Shading SH	1	2	3	1	2	3	1	2	3	1	2	3
S1 Ext	1	1	0	0	0	0	1	1	0	0	0	0
S1 Int	1	0	0	0	0	0	0	0	0	0	0	0
S2 Ext	1	1	1	1	1	0	1	1	1	1	1	0
S2 Int	1	1	0	0	0	0	1	1	0	0	0	0

Orientation	E+W											
Glazing	DH			DL			TH			TL		
Shading SH	1	2	3	1	2	3	1	2	3	1	2	3
S1 Ext	1	1	1	1	1	1	1	1	1	1	1	1
S1 Int	1	1	0	1	0	0	1	1	0	1	0	0
S2 Ext	1	1	1	1	1	1	1	1	1	1	1	1
S2 Int	1	1	0	1	1	0	1	1	0	1	1	0

Orientation	S											
Glazing	DH			DL			TH			TL		
Shading SH	1	2	3	1	2	3	1	2	3	1	2	3
S1 Ext	0	0	0	0	0	0	0	0	0	0	0	0
S1 Int	0	0	0	0	0	0	0	0	0	0	0	0
S2 Ext	1	1	1	0	0	0	1	1	0	0	0	0
S2 Int	1	1	0	0	0	0	1	0	0	0	0	0

Orientation	S+N											
Glazing	DH			DL			TH			TL		
Shading SH	1	2	3	1	2	3	1	2	3	1	2	3
S1 Ext	1	1	1	0	0	0	1	1	1	0	0	0
S1 Int	1	1	0	0	0	0	1	0	0	0	0	0
S2 Ext	1	1	1	1	1	1	1	1	1	1	1	1
S2 Int	1	1	0	1	0	0	1	1	0	1	0	0

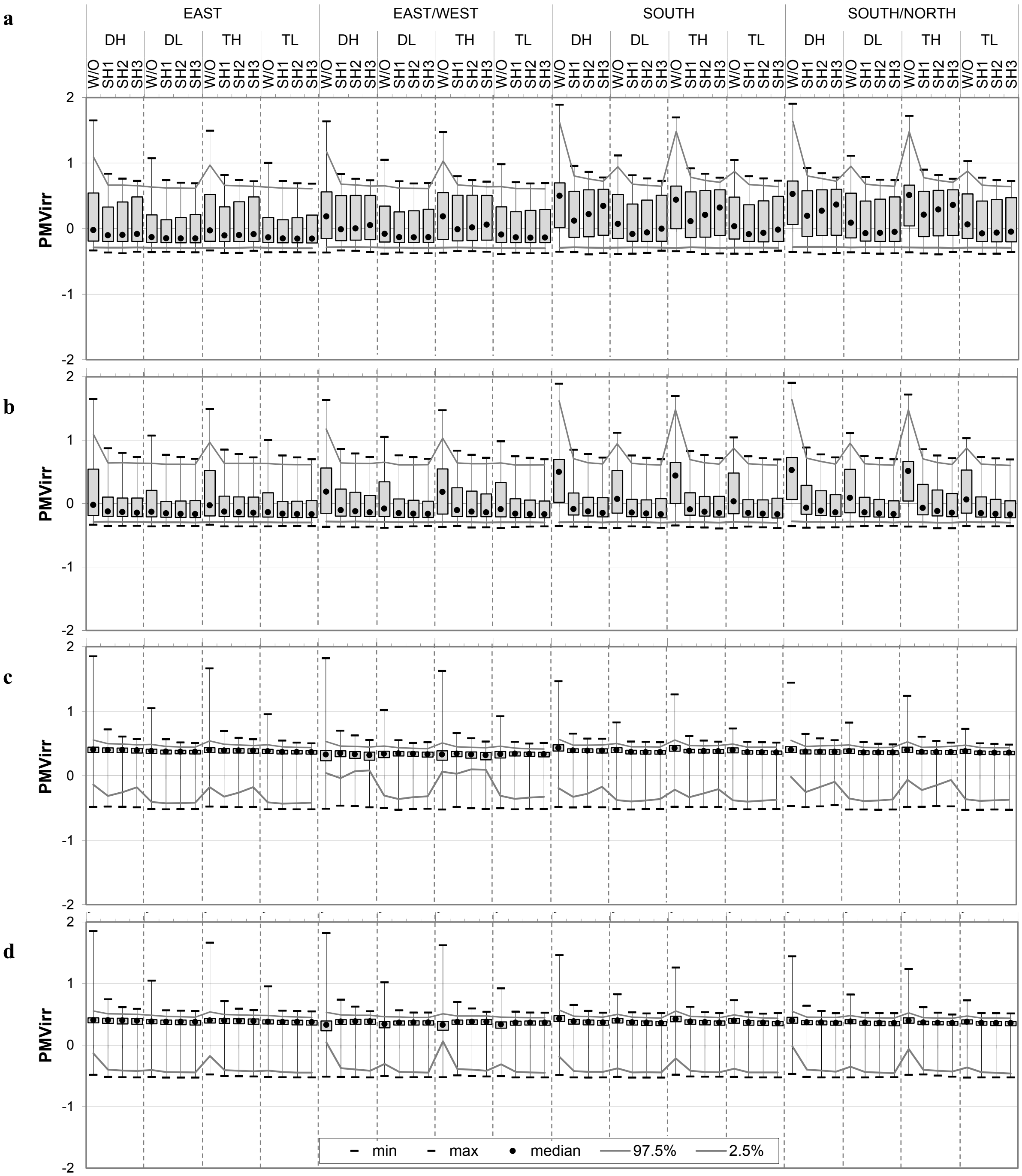

Fig. 2. Cases with small windows: winter distributions of PMV_{irr} for position 2 with internal shades(a) and with external shades (b); summer distributions of PMV_{irr} for position 2 with internal shades (c) and with external shades (d)

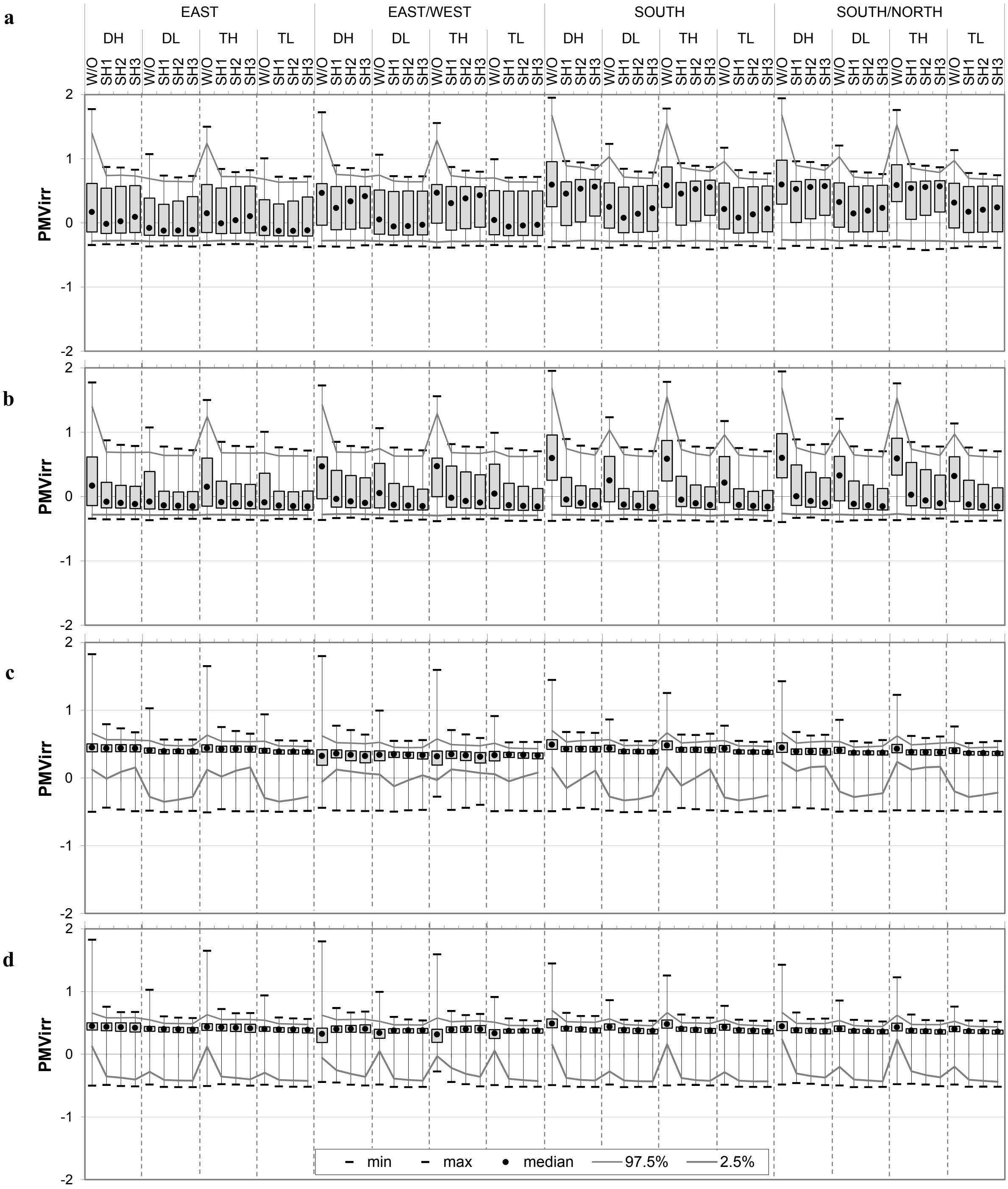

Fig. 3. Cases with large windows: winter distributions of PMVirr for position 2 with internal shades(a) and with external shades (b); summer distributions of PMVirr for position 2 with internal shades (c) and with external shades (d).

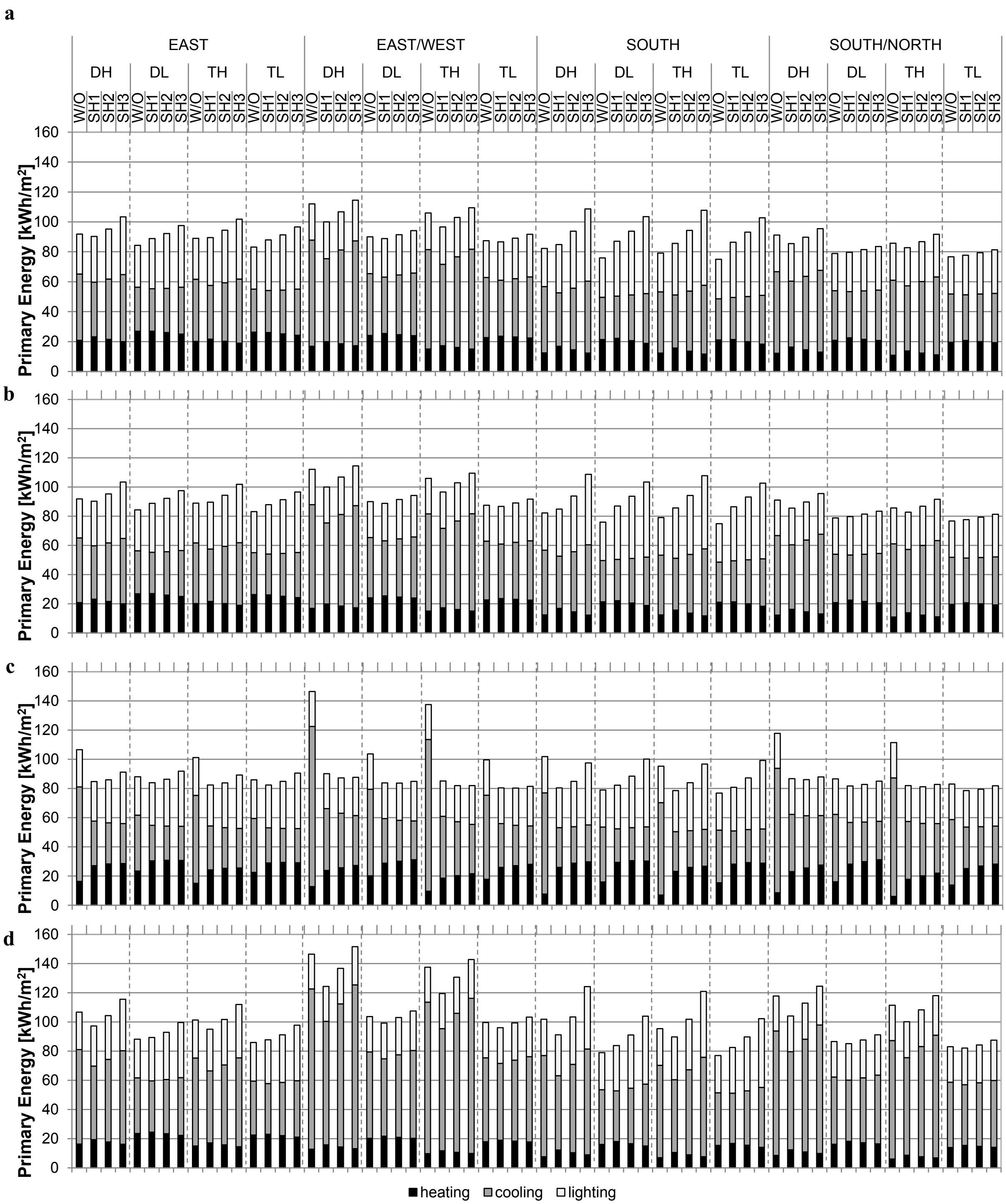

Fig. 4. Cases with small windows: primary energy needs with external shades (a) and internal shades (b); Cases with large windows: primary energy needs with external shades (c) and internal shades (d)

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