Energy performance of shading devices for thermal and lighting comfort in offices

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Abstract

In this paper, the effect of the windows shading systems both on visual and thermal comfort and on the total building energy needs (for heating, cooling and artificial lighting) has been analysed. An open-space office module with different window characteristics has been simulated with EnergyPlus 7.1, controlling the internal conditions with appropriate comfort setpoints. Different window distributions (on a single façade or on opposite façades), and two orientations have been analysed, varying the glazed area and the glazing type. Two moveable shading systems have been considered (roller shades and venetian blinds), controlled by two setpoint variables: the glare index and the total solar radiation incident on the windows.

1. Introduction

The office building category is often characterized by an extensive use of glazing façades. The presence of large transparent components and the application of shading devices have usually been the object of analysis because solar gain values can largely influence the building thermal energy balance both in summer and winter, the lighting energy demand and both the thermal and visual comfort. 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 opaque envelope composition, floor shape ratio, windows area (Eskin and Türkmen, 2008; Shen and Tzempelikos, 2012a; Shen and Tzempelikos, 2012b; Zhu *et al.*, 2013). Tsikaloudaki *et al.* (2012) carried out a similar analysis on a residential building and proposed some correlations.

Some studies focus on the assessment of the thermal and visual efficiency of different shading devices (David *et al.*, 2011 Kuhn, 2006). David *et al.* (2011), calculated by means of dynamic simulations, and evaluate their relation with the solar shading coefficient, cooling energy demand, daylight autonomy and sun patch index on work plane. Tzempelikos *et al.* (2010) introduced a transient thermal comfort model to investigate separately the impact of different shades and three kinds of glazing on mean radiant temperature, operative temperature, thermal discomfort index, radiant asymmetry, and daily heating needs for a perimeter office with a high window area. Two representative days for winter conditions in Montreal (Canada) have been taken into consideration.

The relation between the use of shading devices and availability of natural light was investigated by Kim *et al.* (2012) who suggest that optimal shading systems should increase daylight levels while controlling the amount of excessive sunlight.

The effect of different shading devices has been often analysed considering different control strategies in order to optimize the visual comfort and minimizing the artificial lighting demand (Ihm *et al,* 2011; Mahdavi and Dervishi, 2011; Correia da Silva *et al.*, 2012; Oh *et al.*, 2012). Moreover, some authors optimized the selection of the window size and of the properties of shades with reference to the heating, cooling and lighting energy performance

considering different control strategies (Tzempelikos and Athienitis, 2007).

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 comfort, but only a few authors analyse all these aspects together (Nielsen et al., 2011). By means of dynamic simulation, they calculate the energy demand and the daylight level of a single office comparing different situations of shading (none, fixed, dynamic), modifying some variables such as the orientation and the size of windows. They also imposed an internal setpoint for heating/cooling and air flow rates for mechanical ventilation coherent with the comfort conditions of class II in the Standard EN ISO 15251:2007 (CEN, 2007).

Also, Poirazis *et al.* (2008) used a comfort setpoint strategy for temperature and lighting. A minimum acceptable level for thermal comfort satisfaction was defined.

Finally, Ochoa *et al*. (2012) compared multi-objective optimization criteria for low energy consumption and high visual criteria. Frontini and Kuhn (2012) proposed a new method to evaluate the impact on mean radiant temperature in office spaces of four different internal blinds combined with four kinds of glazing and considering an on-off strategy during two typical days for winter and two for summer.

In this paper, the effect of the windows shading systems both on visual and thermal comfort and on the total building energy needs (for heating, cooling and artificial lighting) of an open office module has been analysed. The thermal comfort has been controlled by fixing the operative temperature setpoint consistent with the comfort conditions of class II of EN ISO 15251:2007. The visual comfort requirements have been taken into account by fixing a maximum limit value for the glare index and a minimum illuminance level to be meet through the shading system control and artificial lighting integration.

The windows have been distributed on a single façade or on opposite façades, and the room oriented towards 2 different orientations, varying the glazed area (2 sizes) and the glazing systems (4 types). Three different moveable shading systems have been compared (two kinds of venetian blinds and roller shades), controlled by two criteria – the glare index and the total solar radiation incident on the windows.

One locality in southern Europe (Rome) has been selected for the investigation. The comfort indexes have been calculated for each hour of occupation of the whole year assuming two seasons as regards the setpoint conditions and clothing level. The evaluation of the long-term comfort conditions (on seasonal basis) has been conducted by computing the hourly value of the Predicted Mean Vote index in 9 different positions in the office and considering some statistical indicators of distribution (the median, minimum, maximum and the interquartile range). The energy performance for heating, cooling and lighting of the different solutions has been compared accounting for comfort considerations. Energetic, comfort and lighting simulations have been carried out with EnergyPlus 7.1.

2. Simulation assumptions

2.1 Office model

The model is an open office space of 100 m^2 of floor area and 3 m of interior height. Vertical walls and roof are exposed to the outdoor environment. The floor is considered as adiabatic, assuming that it is located above a zone with the same indoor thermal conditions.

The composition of all the opaque elements, both vertical walls and roof slab, is identical, with a clay block internal layer 20 cm thick and an external insulation layer 5 cm thick and a thermal transmittance of 0.45 W m^{-2} K^{-1}.

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.

The considered venetian blinds have a high and low reflectivity. A roller shade with 0.4 solar transmittance was evaluated as an intermediate solution between the alone glazing system and the null transmittance of venetian blind, preserving the occupants clear vision of large objects outside. A full

factorial parametrical analysis has been performed by varying the parameters as summarized in Table 1.

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
Glazings	DH: Double Glazings 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 Glazings with high SHGC U_{gl} = 0.613 W m^{-2} K^{-1}; SHGC = 0.575; τ_d = 0.391 TL: Triple Glazings with low SHGC Ugl = 0.602 W m^{-2} K^{-1}; SHGC = 0.343; τ_d = 0.191
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
Window distribu-tion	East (E) East + West (E+W) South (S) South + North (S+N)
External shadings	WITHOUT SHADES (WO): - ROLLER SHADE (RS): Roller Shade; ρ_s = 0.5; τ_s = 0.4 BLIND-H (BH): Venetian Blind with high reflectivity slats; ρ_s = 0.8 BLIND-L (BL): Venetian Blind with low reflectivity slats; ρ_s = 0.2

Table 1 – Variables set for the analysis

2.2 Internal gains and schedule

The office occupation period is from 8:00 am to 6:00 pm, Monday to Friday. According to the Italian Technical Standard UNI 10339:1995 (UNI, 1995) the occupancy index for an open office can be fixed at 0.12 people/m^2, which corresponds to 12 occupants.

The occupants' activity is defined as sedentary with a metabolic flux 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 unit thermal resistance of clothing is 1 clo (such as typical work clothing with long trousers, shirt, tie and jacket) during the winter season, and 0.5 clo (such as lightweight summer trousers and a light long-sleeved shirt during the summer). The conventional winter season is from 1st October to 31st March while the summer season is from 1st April to 30th September.

The considered Light Power Density (LPD) is 12 W m^{-2}, with T-8 fluorescent lamps installed on the ceiling.

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

Lighting and Thermal comfort control

The lights are turned on only during occupation hours. A control system operates on the artificial lighting in such a way that the integration, and consequently the electric power required, increases or decreases continuously and linearly, depending on the level of illumination provided by natural light, in order to maintain 500 lux of illuminance level, as prescribed by EN ISO 12464-1:2002 (CEN, 2002).

In order to guarantee the visual comfort, the shading devices are closed in relation to the amount of incident radiation on the outdoor surface of the windows: when the total radiation overcomes 150 W m^{-2} the shadings are closed. This setpoint value has been chosen considering that people do not 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} (Inoue *et al*., 1998; Farber Associates, 1992; Newsham, 1994; Reinhart and Voss, 2003). Venetian blinds tilt is also controlled in order to reject beam solar radiation. A second control criterion based on the DGI (Daylight Glare Index) is assumed. A DGI limit value of 22 for the position 2 (Figure 1) has been selected, which corresponds to a value of Unified Glare Rating (UGR) of 19 as required by the standard EN ISO 15251:2007 to ensure the comfort of light inside the confined spaces for office use.

The control strategy of the heating and cooling system ensures the compliance with the limits imposed by the EN ISO 15251:2007 or by the EN ISO 7730:2005 by imposing operative temperature conditions during the weekdays within 20°C to 24°C for winter and from 23° to 26°C for summer, which are the described ranges Category II or B respectively, for a normal level of expectation about

the conditions of comfort for users. A setpoint of 15 °C has been considered for the night-time and for weekends. Referring to the cooling setpoints during the unoccupied periods, the setpoint is equal to 38 °C until 6:00 am and then is gradually reduced to the occupational setpoint. To determine the variability of thermal and visual comfort conditions inside the office, a grid consisting of 9 points, each one at 0.8 m from the floor level was considered. For each of these points, specific indicators for the evaluation of thermal and lighting comfort were calculated.

Through the analysis of the spatial distribution of the indices of thermal and visual comfort, it is possible to estimate their variation both from a geometrical point of view, thus evaluating the uniformity of the environment, and over the time period considered.

Figure 1 represents the positions considered for the comfort analysis. For reasons of space, the point P5, located at the centre of square floor, and the points P2 (for South oriented) and P6 (for East oriented buildings), which are the most representative or critical positions have been analysed respectively for the thermal comfort and for the glare discomfort. The comfort conditions have been analysed only during the occupancy period.

2.3 Thermal and daylight simulation

EnergyPlus enables both thermal 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

At the end of the paper the results of the thermal comfort analysis and of the energy simulations have been represented for the winter season (Figure 2) and for summer season (Figure 3). Figure 4 shows the results concerning the indoor glaring and the corresponding energy needs for artificial lighting.

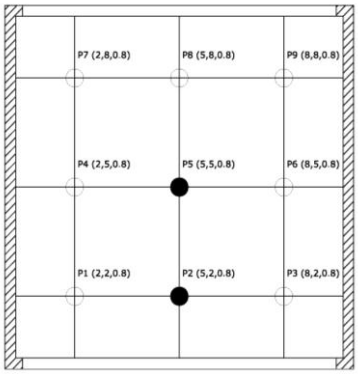

Figure 1 – Plan of the office model and occupants' positions for the PMV calculations (orientation South/North)

3.1 Indoor thermal comfort

In Figures 2a and 2c the distribution of the Predicted Mean Vote for small and large windows is plotted for the winter season. 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 of all the values calculated during the occupied hours. Because of the temperature control strategy, 75% of the PMV values remain, in all configurations, within the range ± 0.5. Nevertheless the PMVs have a greater dispersion during the winter season. The application of the external shading devices reduces the variability of the comfort index.

The standard deviation between the PMV values of each hour over the 9 positions has been calculated and its maximum values during the occupied hours have been evaluated for each configuration.

The maximum standard deviations for the winter and summer seasons have been reported in Table 2 for the windows without shades (WO) and with the different kinds of shades analysed (roller shades/RS, high reflectivity/BH and low reflectivity/BL venetian blinds). It can be seen that the standard deviation never overcomes the value of 0.09 and it decreases when shading devices are used.

	WO	RS	BH	BL
Winter	0.081	0.049	0.036	0.019
Summer	0.089	0.054	0.047	0.030

Table 2 – Maximum standard deviations between the PMV values at the 9 positions all over the office

3.2 Heating and cooling energy use

During the winter season, both heating and cooling needs are present (Figure 2). The use of sun protection systems with the considered control strategy leads to increasing heating needs and decreasing cooling needs. Considering the smaller windows, almost for all the cases the increasing in heating needs overcomes the decreasing in cooling needs. In fact, the shading control results in a reduction of the contribution of solar gains without affecting night thermal losses. However for larger windows, the reduction of cooling needs due to shades overcome the increment of heating needs.

During the summer, heating energy needs are almost null (Figure 3). Shading devices are fundamental for the reduction of cooling needs and elimination of glare. For each shading device, size and kind of glazings, it can be seen that for the E and E/W orientations of windows the cooling energy needs are larger. Regarding the windows size, the larger the windows, the larger the cooling needs, but the increase is not the same in percentage for all the shading conditions: the increment is maximum for glazings without shades (from 107% to 23%) and it is minimum for the venetian blinds with low reflectivity (from 55% to 3%). Roller shades and blinds with high reflectivity have a similar behaviour even if the blinds give the lower energy needs.

Comparing the shaded cases to the ones without shading, the use of glazings with a high SHGC gets the largest advantages from the shading device. Considering the shading devices for the same glazing type, orientation and window size, it can be seen that the best performing shades are the venetian blinds with low reflectivity slats.

Lighting needs and Indoor visual comfort

The annual lighting energy needs have been plotted out computing the number of occupied hours for which the DGI exceeds the limit value of 22 (Figure 4). For reference, annually the hours of occupation are 2500.

Regarding the discomfort from glare associated with configurations without sunscreen, it can be noticed that, for the South or South/North orientation, the hours of glare discomfort are approximately in the range 760-600. This means that the occupants will find themselves under conditions of visual stress for about 30% of their working time (Figures 4a and 4c).

The use of blinds with slats at high or low reflectivity, reduces to zero (or near to zero) the hours of discomfort. As could be expected from the quite large solar transmittance, the roller shades do not allow to reach the same results, with even an increasing time of glare discomfort when considering window size S2 and E or E/W orientation. In general the sun protection systems, if adjusted depending on the amount of radiation incident and on the glare index, lead to an increase of artificial lighting needs. However, the control system set for the artificial lighting is usually able to reduce the consumption of electricity from 30% to 60% compared to a system switched on and off manually (Galasiu *et al*., 2004).

Figure 5 suggests that although the use of shading devices results in an increase in primary energy demand for the winter season in each configuration, their use always leads to a reduction in total needs.

4. Conclusions

In this paper, different shading devices have been compared in relation to the energy needs for equivalent thermal comfort conditions and under an equivalent regulation setup for the glare control. The use of solar shading systems has resulted in an increase in final energy demand for artificial lighting, in the net energy demand for heating mostly in winter, a decrease in net energy demand for cooling during both summer and winter in all configurations. The primary energy need of each configuration allows to compare the overall performance of the different shading systems. The shading system which gives the lowest energy demand is strictly related to the orientation of the windows, to the windows size and position and to the glazing system to which it is coupled. It is quite difficult to generalize the results in terms of optimal configuration, but it is clear that for Rome's climatic conditions the shading devices are essential to contain the total primary energy demand and limit glare. Further investigations will be carried out on different roller shades, configurations and climatic context.

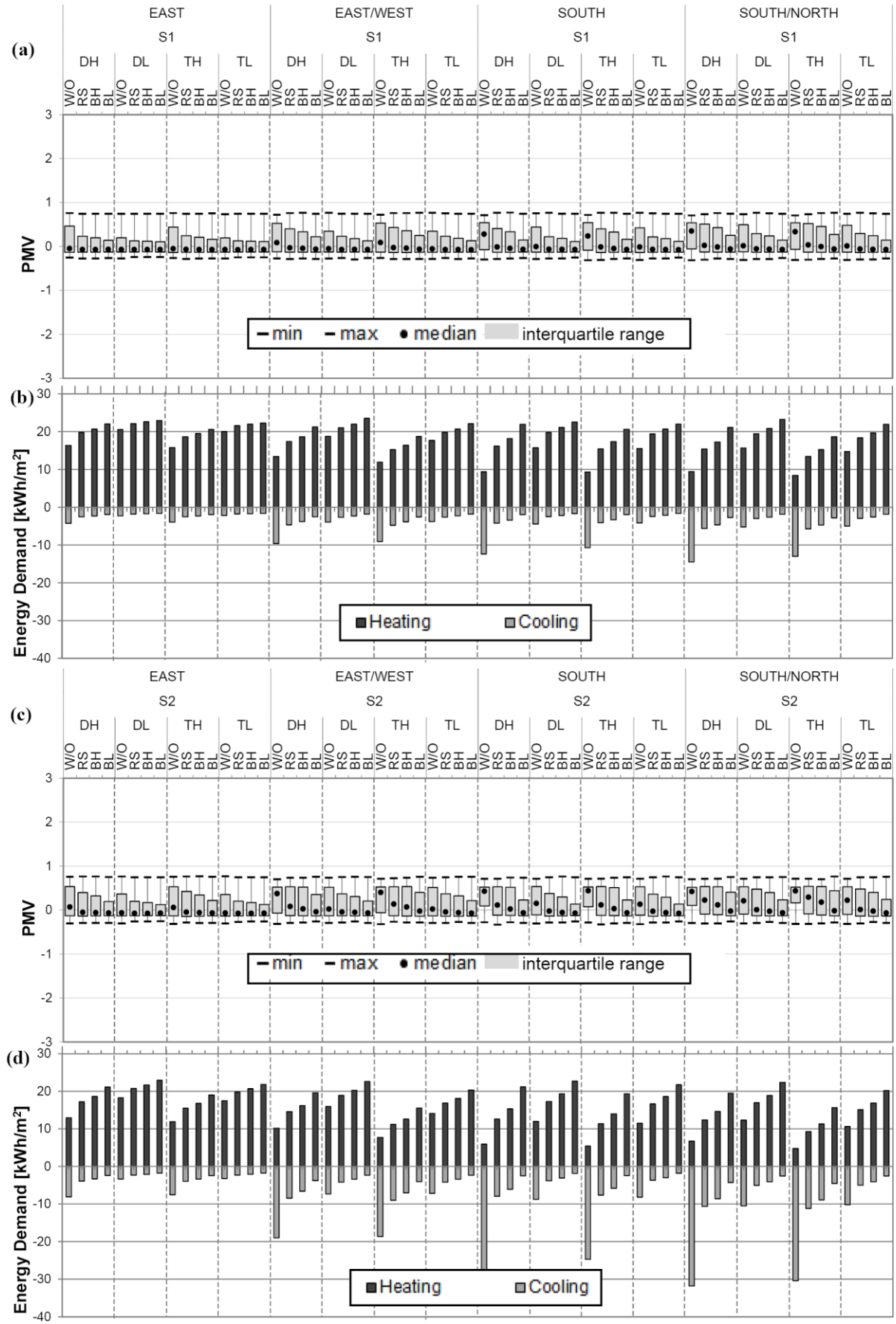

Figure 2 – Winter distributions of PMV for small (a) and large windows (c) and Energy needs for small (b) and large windows (d)

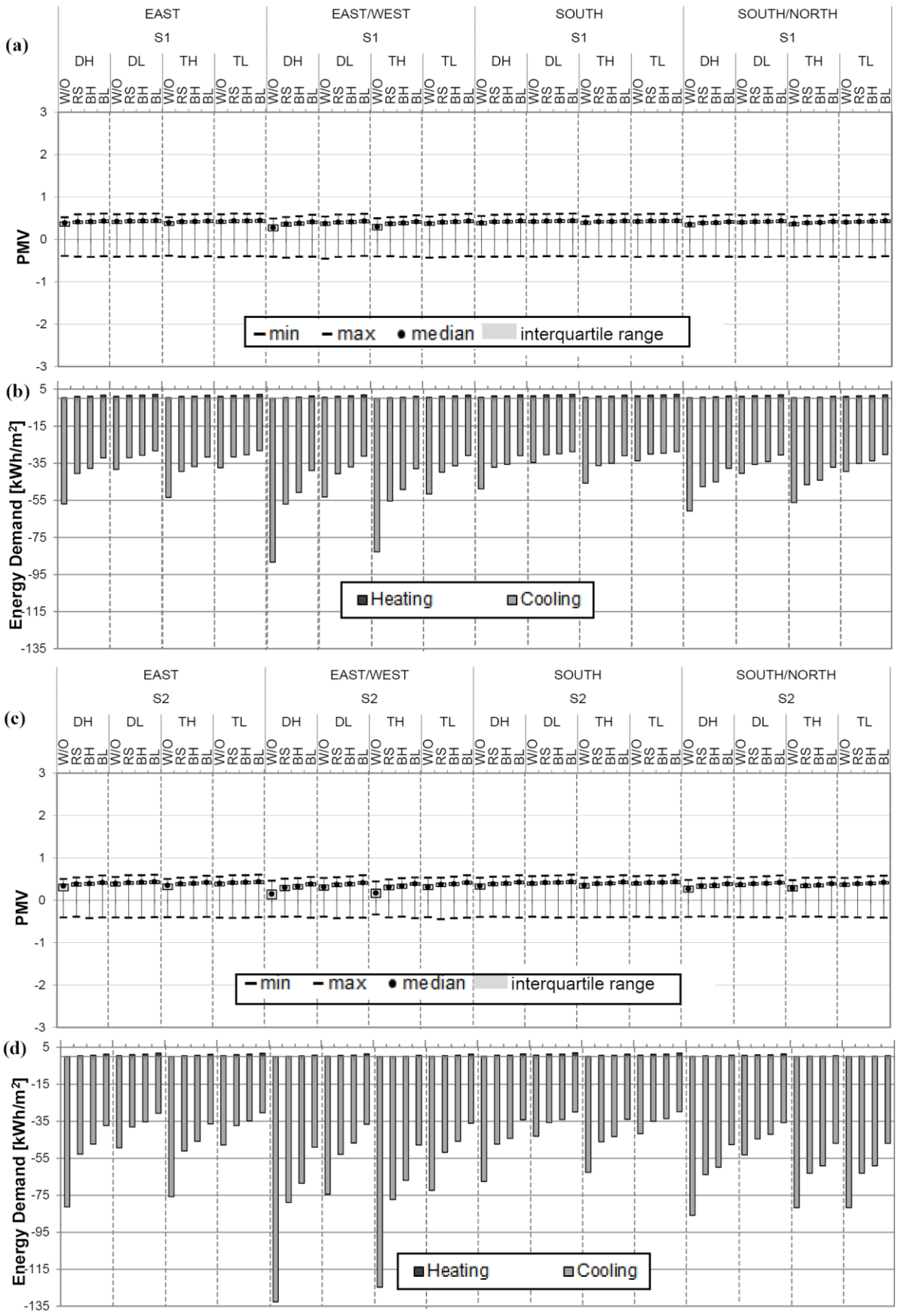

Figure 3 – Summer distributions of PMV for small (a) and large windows (c) and Energy needs for small (b) and large windows (d)

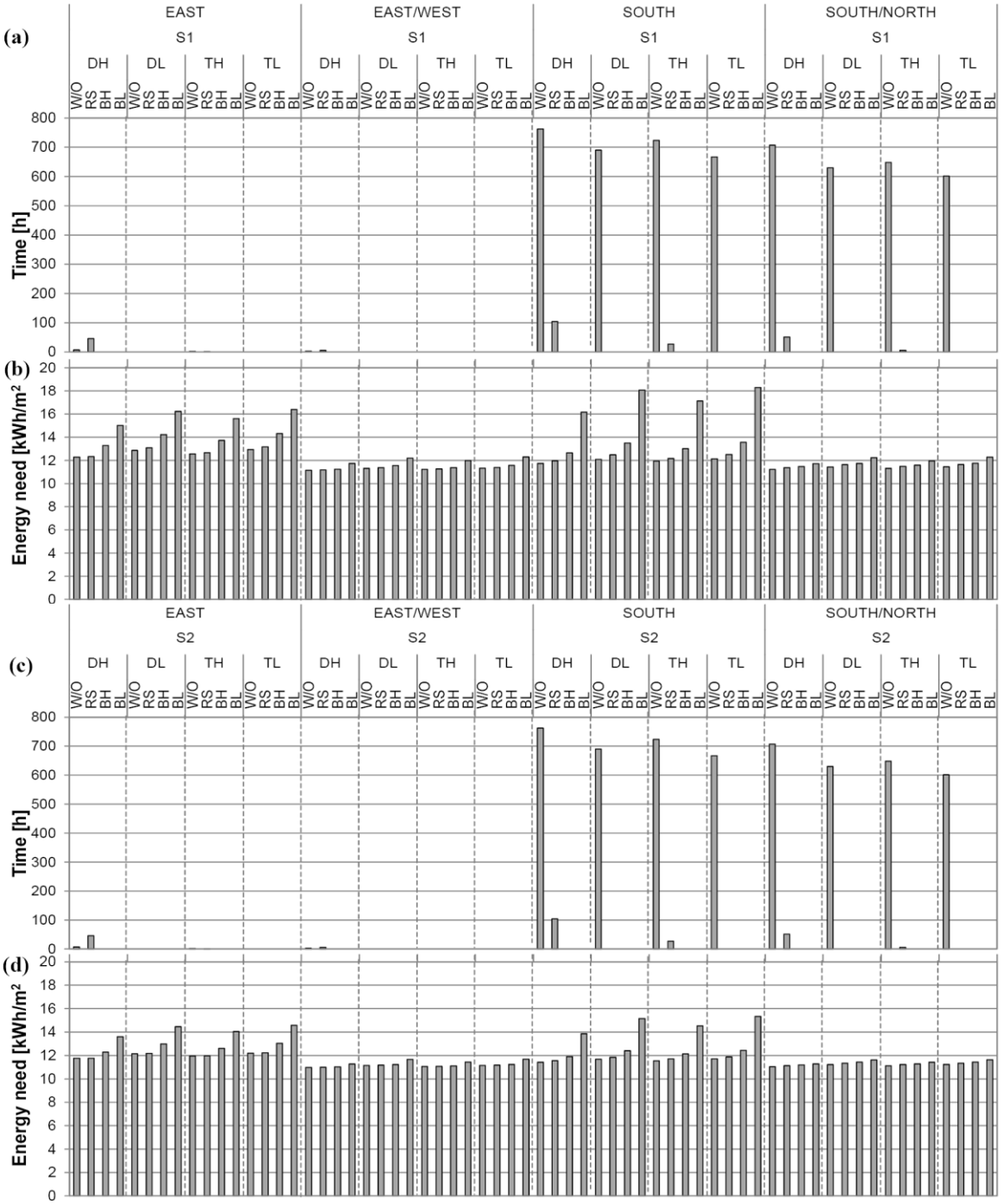

Figure 4 – Hours of visual discomfort and lighting energy needs for small (a,b) and large windows (c,d)

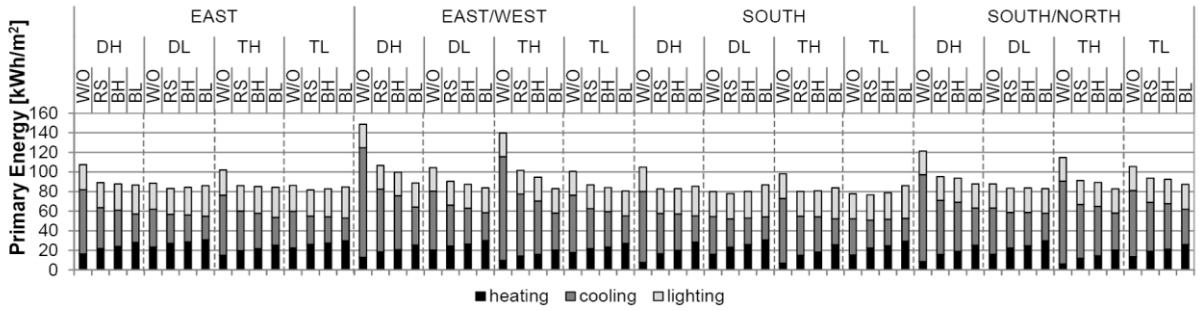

Figure 5 – Total Primary Energy need for larger windows (S2)

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