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Research paper

TRANSPARENT COMPONENTS OF BUILDING FACADES: METHODS AND METRICS FOR AN INTEGRATED EVALUATION OF THE PERFORMANCE OF GLAZING AND SHADING SYSTEMS

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ABSTRACT

The evaluation of the energy performance of transparent components should not neglect their influence on the indoor thermal and visual comfort conditions. If the design choices are based only on the energy need optimization or the cost reduction, they could lead to solutions not suitable for the occupants' comfort. The available design tools allow the realistic and detailed evaluation of the building energy performance in standardized use conditions, once the site climatic characteristics, the envelope thermophysical properties and the technical characteristics of the systems are known. The actual energy performance becomes more difficult to assess when the occupants behavior has to be included, as it is often influenced by their environment's perception and the resulting reactions. The significant effect, often negative, of the occupants' interaction on the real building energy consumption during its operational life, leads to the necessity of a careful assessment of both the building energy needs and the comfort conditions at the same time, since the early design phase. The use of indicators and metrics able to synthesize the different fundamental aspects of the performance, including the indoor environmental quality, becomes essential in order to carry on an adequate comparison between different options.

Keywords: Thermal comfort, visual comfort, daylight autonomy, comfort metrics, shading and window systems, integrated performance evaluation

Introduction

The transparent components play a complex role, which is characterized by different functions and by a close interaction with the rest of the envelope and with the occupants. First, they have to allow the occupants a direct visual contact with the outdoor environment, without compromising the visual comfort and preventing glare from solar radiation. Moreover, they have to facilitate the deployment of daylighting while controlling solar gains. Finally, as any other envelope component, they have to guarantee thermal insulation and air tightness, either in the heating or in the cooling seasons.

Satisfying all those requests through as single transparent element is almost impossible, without the recourse to a combination of glazing and shading systems, properly controlled and operated. In this respect, the optimal design and operation has to consider the building characteristics in terms of size and orientation of the openings, envelope properties, use and occupants' expectations, and the specific climate. This complicated task requires a careful evaluation and a suitable balance of several contrasting needs.

Two elements are needed to a correct analysis and comparison of the design options: the capability of model the different aspects involved in a detailed and integrated way, and the possibility of assessing and comparing in both their time and space distribution the different performance through suitable metrics.

There are relatively few works in literature dealing with the integrated analysis of transparent systems, considering both the different energy (heating, cooling and lighting needs) and the thermal and visual comfort aspects. In most of the cases, thermal comfort metrics do not account for the effects of solar radiation on the occupants, neglecting quite often also the space distribution.

Almost all the works focus on office buildings performance, considering the effects of different parameters (geometric, thermal and visual characteristics of glazing systems, shading and artificial lighting systems' control strategies) on energy needs and/or on thermal and visual comfort. Without entering into details on the specific parameters used, the research papers can be distinguished in four groups, depending on the aspects evaluated:

- Control strategies for shading systems and energy needs for cooling (Tsikaloudaki *et al.*, 2012), for heating and cooling (Eskin and Türkmen, 2008, Poirazis et al., 2008, Kim *et al.*, 2012), and for cooling, heating and lighting (Correia da Silva *et al.*, 2012) or kinds of external shades and cooling and lighting energy needs (Bellia et al, 2013);
- Visual comfort and energy needs for cooling and lighting (Tzempelikos and Athienitis, 2007, David et al., 2011,), or for cooling, heating and lighting (Ochoa et al., 2012, Oh et al., 2012, Shen and Tzempelikos, 2013, Tzempelikos and Shen, 2013);
- Thermal comfort and energy needs for heating (Tzempelikos et al., 2010a and 2010b), cooling (Hwang and Shu, 2011), heating and cooling (Buratti et al., 2013, Cappelletti et al., 2014), or heating, cooling and lighting (Nielsen et al., 2011);
- Visual and thermal comfort, energy needs for heating and cooling (J. Yao, 2014), or for heating, cooling and lighting (Shen and Tzempelikos, 2012)

In this work, the behavior of different transparent systems, consisting of glazings and shades, are analyzed, considering the different aspects listed above and proposing some metrics able to synthesize the performance and to support the comparison and the choice. A reference building module with a floor area of 100 m^2, and dedicated to an office use, in the geographic and climatic context of Rome has been considered in order to assess the methods and to generalize some conclusions about the optimal configuration results, with respect to the orientation (East or South) and the size of the windows. Three kinds of shading systems with different reflection and transmission properties and four kind of glazings have been combined to evaluate their interactions.

1. Methods

To represent realistically the behavior of a building and in particular to understand how the overall performance is affected by the variability of the solar radiation, not only along the year, but within each single day, it is necessary to deploy dynamic simulation codes.

Moreover, an integrated approach to the analysis of the effects of solar radiation entering indoor spaces, able to include both the energy and the thermal and visual comfort aspects, currently requires the use of different simulation tools. Some works (Ramos & Ghisi, 2010) demonstrate that the analysis by means of EnergyPlus can lead to an overestimation of daylighting and a subsequent underestimation of the artificial lighting needs.

In order to overcome this situation, in this paper besides the EnergyPlus energy simulation, the lighting analysis of each configuration has been implemented by means of DIVA, which uses Radiance and DAYSIM calculation algorithms. The daylight illuminance and glare trends calculated by DIVA have been processed through a MATLAB code in order to calculate the control profile for shading devices and artificial lights based on the visual comfort and illuminance thresholds. These last control profiles have been used as inputs for the EnergyPlus simulation to calculate the primary energy needs and the useful data to calculate the thermal comfort indexes. The diagram in Figure 1 shows the whole simulation procedure.

2. Reference buildings

A set of reference buildings has been obtained introducing some variations to a building module of 100 m^2 and an internal height of 3 m, located in Rome (climatic zone D), and used as open-space office. The choice of studying an office building instead of other types of buildings is due to different considerations: a great number of modern commercial buildings usually characterized by wide windowed facades, a high importance of the right lighting level and glare control, a limited possibility of managing the occupants working stations, and finally a high amount of internal gains.

Concerning the envelope characteristics, all the opaque elements are composed of an indoor layer of bricks and outdoor insulating layer, 0.1 m thick, with a thermal transmittance equal to 0,28 $W{\cdot}m^{-2}{\cdot}K^{-1}$. The insulation thickness is such as to assure the respect of the requirements imposed by the Italian Law D.P.R. 59/09 for buildings built in climatic zone D. All the envelope surfaces are supposed to be exposed to outdoor conditions except for the floor, which has been simulated as a boundary element between the simulated zone and a zone with the same temperature.

The reference module has been changed trough some alternatives as for the geometrical area of windows, their orientation, the type of glazing system double or triple pane), the optic characteristics of the shading devices and their location (indoor or outdoor). The combination of all this variations (Table 1) has led to 64 configurations in total. Concerning the choice of shading devices, roller shades have been chosen because of they are commonly used in office buildings due to their practical installation and management even in case of building energy retrofit.

Table 1 - Configuration variables used in the reference buildings

Element	Code	Values/Thermal properties
Windows dimensions	S1: S2:	width = 9; height = 1,5 m; area = 13,5 m^2; WWR 45% width = 9; height = 2,5 m; area = 22,5 m^2 ; WWR = 75%
Orientation	E: S:	east oriented windows only south oriented windows only
Glazing systems	DH: DL: TH: TL:	U_{gl} = 1,14 $W{\cdot}m^{-2}{\cdot}K^{-1}$; SHGC = 0,60; τ_{vis} = 0,81 U_{gl} = 1,08 $W{\cdot}m^{-2}{\cdot}K^{-1}$; SHGC = 0,35; τ_{vis} = 0,58 U_{gl} = 0,60 $W{\cdot}m^{-2}{\cdot}K^{-11}$; SHGC = 0,59; τ_{vis} = 0,73 U_{gl} = 0,61 $W{\cdot}m^{-2}{\cdot}K^{-1}$; SHGC = 0,35; τ_{vis} = 0,63
Roller shades	W/O: SH: SH2: SH3:	without roller shades ρ_s = 0,58; τ_s = 0,16; ρ_v = 0,51; τ_v = 0,15 ρ_s = 0,37; τ_s = 0,10; ρ_v = 0,35; τ_v = 0,10 ρ_s = 0,13; τ_s = 0,05; ρ_v = 0,06; τ_v = 0,05

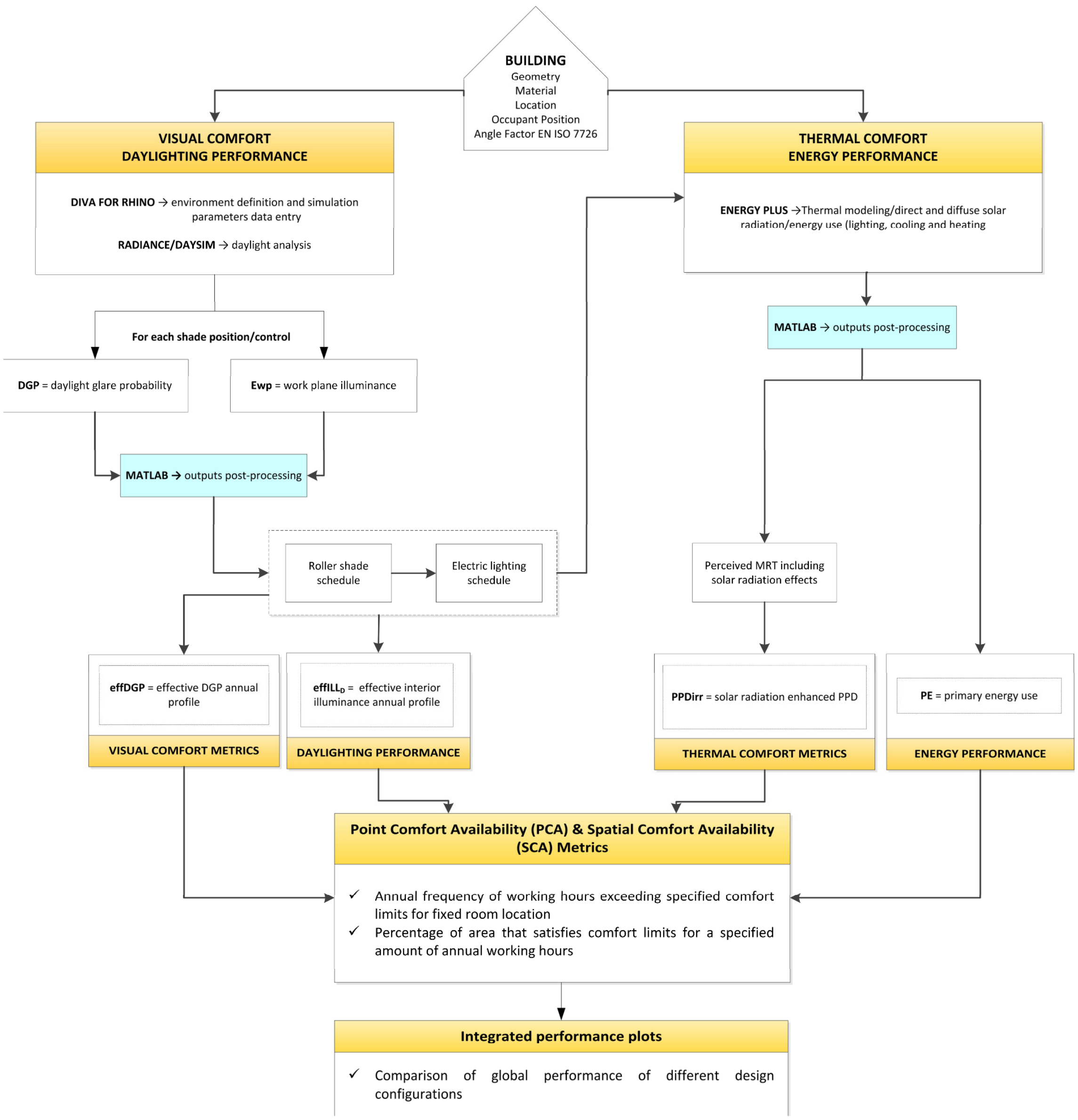

Figure 1 – Calculation procedure of the global performance of the considered building modules.

The office is occupied from 8 A.M. to 6 P.M., from Monday to Friday, with a density of 0,12 people on each square meter of floor. The subsequent internal gains (ASHRAE, 2009) are estimated in 130 W per person, divided into 75 W of sensible quote and 55 of latent contribution. The Electric Power Density has been fixed in 12 $W{\cdot}m^{-2}$ for artificial lighting and 1,31 $W{\cdot}m^{-2}$ for appliances. The ventilation rate has been estimated in 1,58 ACH during the occupancy hours and 0,3 ACH when the office is closed.

The thermal comfort calculation has been developed considering a clothing resistance of 1 clo during the winter semester from 1st October to 31st March and 0,5 during the summer semester, in accordance with the control strategy used for the system.

3. Comfort indexes and energy performance

The actual ability of the control systems in assuring adequate indoor comfort and, at the same time, the energy consumption, has been assessed by means of two types of non-standardized metrics, proposed by authors:

- Point Comfort Availability (PCA) metrics:
- Spatial Comfort Availability (SCA) metrics: are the percentage of floor area on which the PCA values (that is temporal frequency of comfort availability) are higher that a minimum, during the reference period of time.

Both the metrics allow representing the performance evolution during a reference period (i.e. a day, a season or a year). The PCA metrics can be plotted on positions distributed inside a mesh located over the floor, usually on the working plane. In Figure

given a specified position, they can provide a quantitative evaluation, considering a reference period, of the temporal frequency during which the comfort levels follow a threshold or an interval considered suitable.

2, the positions considered for the analysis are 9. In this way, it is possible to evaluate the comfort condition variability from a geometrical point of view and to check their different entity in the space.

The SCA metrics on the other hand side, provide a single numerical value describing the performance, summarizing for the space the indication given by PCA metrics.

Given their meaning, all the comfort metrics and their evolution should be evaluated only during the occupancy hours.

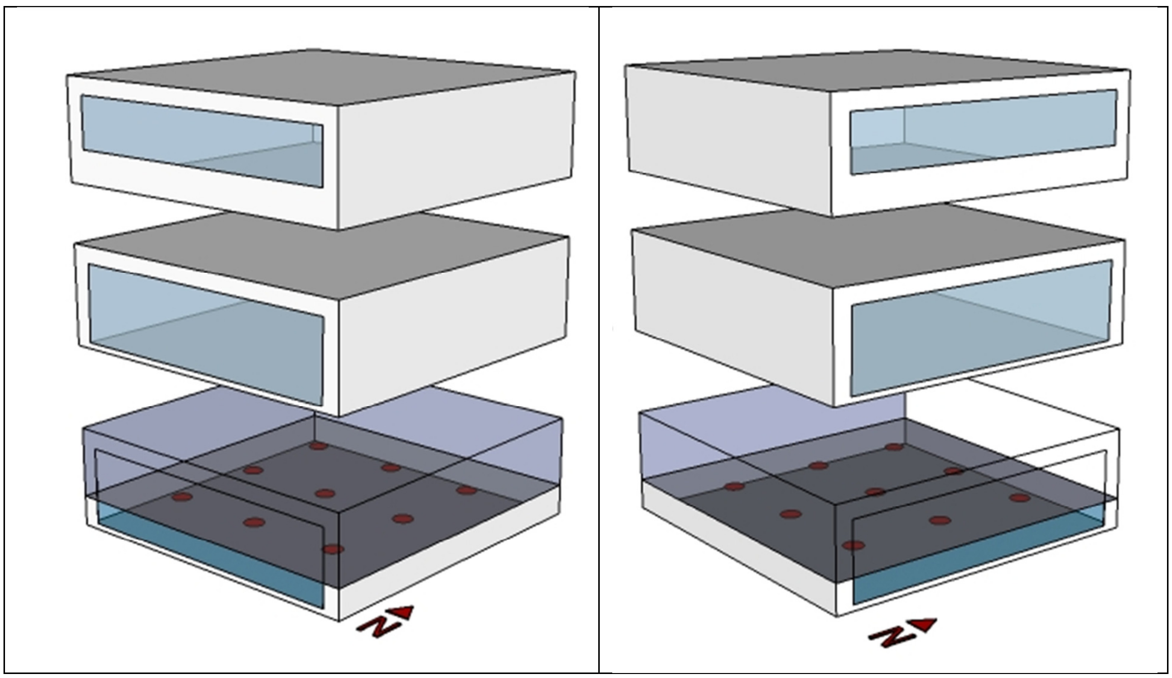

Figure 2 – Sketch of the simulated office building: configuration with S1 windows' size (small) – above; with S2 windows' size (large) – middle; section plane with the position of the grid of points considered in the comfort analysis – below.

Since the aim of this research is to find not only a method for the integrated building performance analysis, but also a graphical representation useful for comparing different design alternatives, the SCA metrics can be considered a good tool to plot tables which allow to compare a substantial number of cases on a quick view.

The ability of the indoor environment of using the daylight has been expressed with the Daylight Autonomy or DA, defined as the percentage of occupancy hours during which, on one specific point in the space overtakes, with daylight only, an illuminance threshold, fixed in this work in 500 lux (CEN, 2007, Olbina and Beliveau, 2009). Reinhart and Weissman (2011), in their analysis on lighting perception, have proved that this metric, chosen by IESNA, gives a good correlation with people perception, even if the better threshold to represent subjective sensation seems to be 300 lux. As a corresponding SCA metric, the spatial Daylight Autonomy, sDA (IESNA, 2012), has been used because it is the floor area The visual comfort has been analised through the Daylight Glare Probability, DGP (Wienold & Christoffersen, 2005, 2006), which is able to estimate the possibility of glare discomfort caused by daylighting. The equivalent PCA metric proposed, is called Visual Comfort Availability (VCA_{DGP}), consistently with the DA meaning and definition. The VCA_{DGP} is the percentage of occupancy hours during which, the DGP on one specific point in the space does not exceed 0,35, that is the limit value above which a glare is considered disabling (CIBSE, 2014). The correlated SCA metric can be called spatial Visual Comfort Availability ($sVCA_{0,35,90\%}$), which expresses the working plane percentage at 0,8 m above the floor on which, during the occupancy hours, the visual comfort conditions are maintained for at least 90% of time.

The thermal discomfort can be described by the Predicted Percentage of Dissatisfied, PPD. In accordance with the other metrics, in this research, it has been decided to represent the percentage of satisfied people (e.g. 100% complement of dissatisfied), in order to highlight the ability of the configurations analyzed to guarantee suitable thermal comfort conditions. The Predicted Mean Vote, from which the PPD is obtained, has been calculated with an hourly time-step in all the 9 position of the mesh (Figure 2), at 0,6 m above the floor, starting from the air temperature and humidity evaluated in the center of the office, considering an air velocity of 0,1 m s^{-1} and a metabolic rate of 1,2 met. The influence of the solar radiation striking the occupants has been taken into consideration calculating a corrected mean radiant temperature, in each of the 9 positions inside the office, which is a function of the direct and diffuse solar radiation and of the angular factors of the seated person, according to the method described by La Gennusa et al. (2007), Atzeri et al. (2015).

The PCA metric proposed for the thermal percentage on which the illuminance overtakes the illuminance threshold for a given percentage of occupancy hours, e.g. 50%. This means that sDA is the are fraction on which the DA overtakes the 50%.

comfort analysis is, therefore, the Thermal Comfort Availability (TCA_{PPD}), which is the percentage of occupancy hours during which, the percentage of satisfied, on one specific position in the space, is at least 90%. The reference PPD value for buildings comfort Category II, according to EN ISO 15251 (CEN, 2008), is, in fact, 10%. The SCA metric, has been called spatial Thermal Comfort Availability ($sTCA_{90\%,90\%}$), and expresses the surface percentage at 0,6 m above the floor on which, during the occupancy hours, the PPD does not exceed 10% for at least 90% of occupancy hours.

The energy performance, has been evaluated by means of the Energy Performance (EP) which is the primary energy need expressed in $kWh{\cdot}m^{-2}{\cdot}yr^{-1}$ and calculated as the sum of the energy need for heating, cooling and lighting, using a global efficiency of 0,8 for the heating system, an Energy Efficiency Ratio (EER) of 3 for the cooling system and a conversion factor of 2,174 for electric energy, as prescribed by the Italian Authority for Electric Energy and Gas (AEEG). The EP metric is suitable to compare the performance of the different configurations immediately. Moreover, the choice of controlling the heating and cooling systems by means of the operative temperature in the center of the office (Cappelletti et al., 2014), allows to consider the energy need as an indicator of the envelope passive performance, because it is an estimation of the management cost, requested by a specific configuration, to guarantee defined thermal comfort conditions. Finally, in this way the thermal comfort conditions in the configurations analyzed differ only due to the different solar radiation that can reach the occupants increasing his/her discomfort. The energy saving reached by means of the shading device, has been calculated as the percentage reduction of the primary energy need of each configuration with the similar configuration without shades.

Table 2 - Equations for the calculatin of the air setpoint

Season	Operative Temperature	Variable Air Set-point
1 October – 31 March	20°C	$T_a = -1.52 \cdot T_r + 2.52 \cdot 20$
	23°C	$T_a = -1.52 \cdot T_r + 2.52 \cdot 23$
1 April – 30 September	24°C	$T_a = -1.52 \cdot T_r + 2.52 \cdot 24$
	26°C	$T_a = -1.52 \cdot T_r + 2.52 \cdot 26$

4. Control strategies

To ensure suitable indoor comfort conditions, both visual and thermal, the dynamic components of the building, i.e. the shading systems, the artificial lighting and the heating/cooling system, have to be able to react to the external and internal solicitations.

Considering the requisites from the technical standards (CEN, 2007; 2011), the luminous flux and, proportionally, the electrical power absorbed by the artificial lighting system have been varied, as a function of the daylighting contribution, to provide a minimum illuminance of 500 lux on the working plane, measured in the three positions on the North-South and on the East-West axis for the South and East orientations respectively (Figure 2).

The position of the shades, completely open or completely closed, is decided as a function of the natural illuminance on the point closest to the window (Figure 2), and of the possible glare conditions. The reference setpoints are respectively the range 500-2000 lux and a maximum Daylight Glare Probability (DGP) equal to 0,35. The latter represents the percentage of people potentially annoyed by the natural light entering the room and by its interaction with the room itself.

As for the thermal comfort, the references are the values suggested by the technical standard EN ISO 15251 (CEN, 2007) for the class II. As already discussed, the year has been divided into two semesters, as for the clothing thermal resistance, I_{cl}, with the system providing heating or cooling the all year, to maintain the operative temperature within the corresponding comfort range. In particular, the inlet air is controlled to maintain the operative temperature in the middle of the room in the ranges 20 ÷ 24 °C for I_{cl} = 1 clo, 23 ÷26 °C for I_{cl} = 0,5 clo. The relation between the air temperature, Ta, the mean radiant temperature, TMR and the operative temperature, To, is described by equation 1, whose coefficients are in agreement with the technical standard EN ISO 13790:2008:

$$T_a = -1.52 \cdot T_r + 2.52 \cdot T_o \qquad (1)$$

The equation 1, allowed to determine the setpoint air temperature as a function of the hourly mean radiant temperature, depending on the reference operative temperature of the corresponding season (Table 2).

During the non occupation period, the system is operated only if the operative temperature lies outside some reference temperature, i.e. a minimum value of 15 °C, and a maximum value, which depends on the hour of the day. This is 38 °C from 18:00 to 24:00 and it then gradually reduces to 28 °C at 8:00.

Since the operative temperature is considered to be in relation to the occupants' thermal comfort, using it as a setpoint also means comparing the different design configuration under equivalent comfort conditions.

5. Results

5.1 Daylighting performance

The availability of daylighting is not affected by the shades' position (internal vs external). Using shades leads to a reduction in the number of hours in which the target illuminance of 500 lux on the working plane is achieved by means of daylight. This reduction (Figure 3 and 4) seems more significant when considering the smaller windows, and increases while moving further from the transparent surface, and for a given kind of glazing, while reducing the shades transmission coefficient. Comparing the two orientations, the South (Figure 4) allows a higher lighting autonomy, also for points not so close to the window. Obviously, this trend is shown also by synthetic metric sDA (Figure 5), from which it can be concluded that the South oriented windows allows a higher luminous autonomy along the entire year than the East oriented ones.

5.2 Visual comfort

Also the visual comfort seems not affected by the position of the shades. In this analysis the occupants' orientation has been assumed as the one which reduces the glare from daylighting, i.e. according to a direction parallel to the luminous source (the windows). This make also the configuration without shades not very far away from the threshold glare values, for the East orientation (Figure 6 and 8). Considering the same indicator PCA for the South oriented windows (Figure 7), the selected occupants' orientation and the use of the shading systems are not enough to avoid discomfort in the points closest to the windows. From the synthetic indicator, it is possible to understand that it is not possible to maintain the desired comfort conditions all over the considered space, when considering the South oriented windows (Figure 8). The configurations without shades South oriented (Figure 7) make it possible to assess the role of the different glazing systems. The discomfort in the points closest to the windows is reduced by 20 % when moving from high to low visual transmittance τ_{vis} glazings.

5.3 Global thermal comfort

Considering the PCA indicator, the points closest to the windows are those which experience the lowest number of comfort hours, especially for the South orientation (Figure 9).

No matter if East or South (Figure 11), the configurations without shades give better comfort conditions only when the low solar transmittance DL or TL glazings are considered. Adding shades, especially for the East orientation, improve the performance, in particular for externally mounted systems (Figure 11). Even if some critical situations are still observed for the largest windows, the room is characterized by a higher thermal uniformity. For the South orientation, in contrast, even if the increase of the comfort hours is larger for the single point, for the external than for the internal shades, the global performance is better with internal shades (Figure 10). In this respect, it is necessary to underline that the PCA accounts for both, heat and cold sensations. This means also that if the two situation were distinguished, the use of external shades reduces the entering solar radiation, especially in the mid seasons, and produces cold discomfort.

5.4 Energy demand

As for the primary energy needs, the external shades (Figure 12, 13 and 14) reduce the overall needs by limiting the cooling ones, in both the orientations. Between the two, the South orientation shows lower needs (Figure 13) than East (Figure 12), also because of the possibility to reduce lighting needs.

The use of shades always increases the heating needs, since the solar gains are reduced. Considering the overall energy performance in the two orientations (Figure 14), the configurations with shades and South oriented windows almost always reduce the needs with respect to the corresponding case without shades. The same is not valid for the East orientations, in which the cooling needs reduction is less than increase of the heating and lighting needs.

6. Conclusions

As mentioned in the introduction, the energy analysis of a building should distinguish the performance between standard use and real use. When the latter is considered, the occupants' behavior and their interactions with the building are a factor of crucial importance. Thermal and visual comfort conditions contribute to the limitation of this factor, making the performance assessment even more reliable. When the indoor environment comfort does not meet the

occupants' expectations, the occupants tend to interact with the building, to improve the comfort conditions, not necessarily considering the optimal energy operation.
It is quite clear that a proper evaluation of the indoor environment, including daylighting, visual, glare and thermal comfort, while maximizing the energy performance is extremely important for a successful design.
One of the main difficulties in the in the assessment of the integrated performance is related to the lack of parameters suitable to quantify but also describe it, in consideration of its variability in time and space. To overcome this issue, two families of metrics, the Point Comfort Availability (PCA) and the Spatial Comfort Availability (SCA), have been described.
The PCA metrics are point indices able to represent and map the comfort conditions over the occupied space, depending on the position of the user. If they can support the choice of the window system most suitable to allow an adequate time availability of comfort in the largest part of the space, they also represent a useful tool to study the possibility to use the space, in order to maximize the overall performance of the building.
The space metrics (SCA), allow the expression through a single parameter of the performance of the entire room, in a given period. They help compare and select the design alternatives, whatever dealing with the glazing, shading or window system or with any other aspect with an influence on the comfort conditions.

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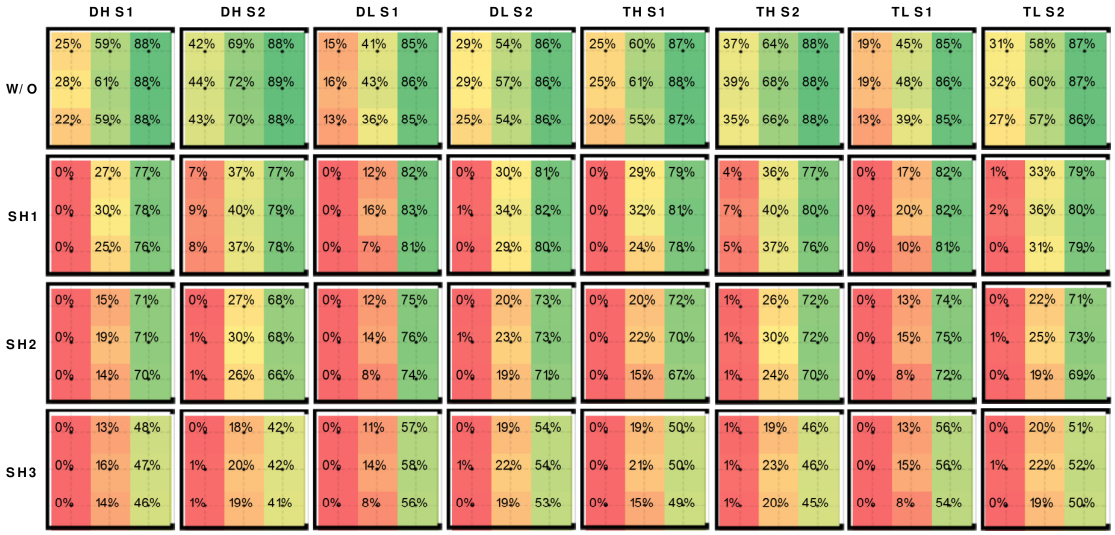

Figure 3 - Daylight Autonomy distribution for East orientation and external shades. Each square represents the plant of the office with the window on the East side (symbols are explained in Table 1).

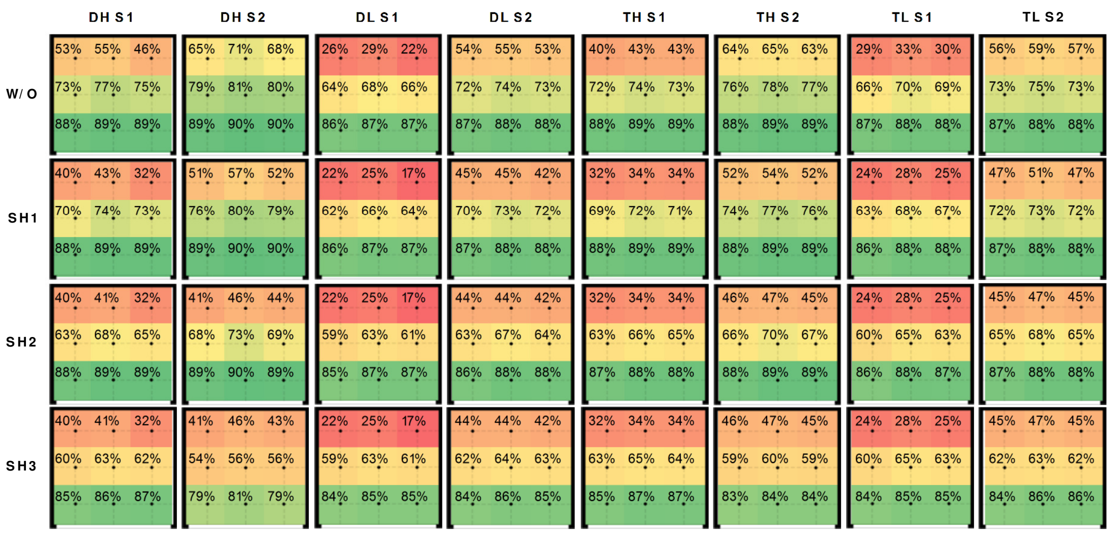

Figure 4 - Daylight Autonomy distribution for South orientation and external shades. Each square represents the plant of the office with the window on the South side (symbols are explained in Table 1).

Configuration	$sDA_{500,50}$																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH
E_S1	56	44	56	44	37	33	38	33	33	31	32	32	11	22	20	22	37	33	36	33	32	31	32	32	11	22	17	22
E_S2	73	56	67	56	44	40	42	38	33	33	33	33	11	22	11	21	41	38	41	38	33	33	32	33	10	22	11	19
S_S1	89	65	78	67	73	59	67	64	67	59	67	63	67	59	67	63	72	60	67	65	67	59	67	63	67	59	67	63
S_S2	100	95	100	98	91	78	96	84	67	77	75	78	59	77	75	78	93	78	95	85	67	77	75	78	59	77	75	78

Figure 5 – Spatial Daylight Autonomy (%) for East and South orientations in the different configurations analyzed (symbols are explained in Table 1).

Figure 6 – Visual Comfort Availability distribution for East orientation and external shades. Each square represents the plant of the office with the window on the East side (symbols are explained in Table 1).

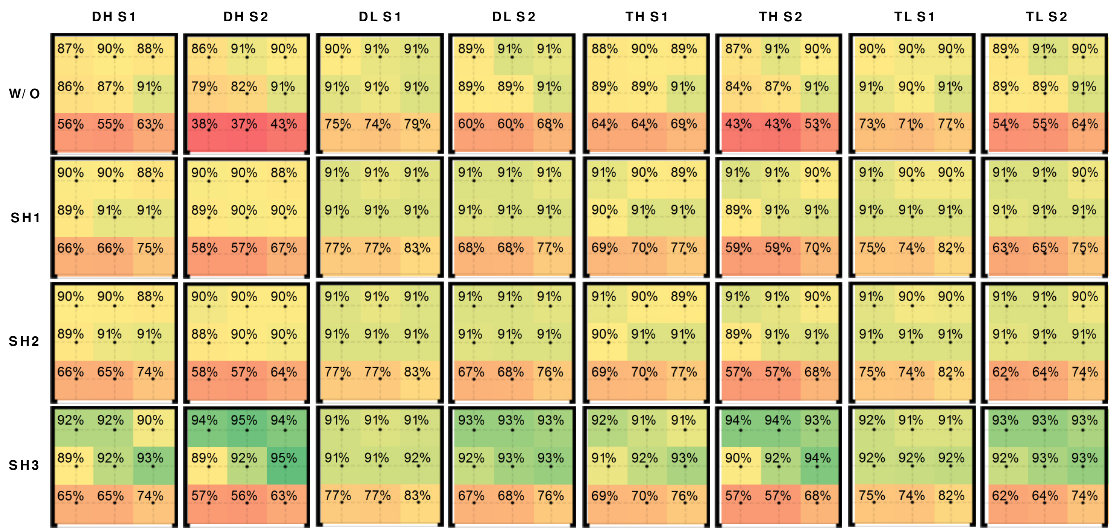

Figure 7 – Visual Comfort Availability distribution for South orientation and external shades. Each square represents the plant of the office with the window on the South side (symbols are explained in Table 1).

Configuration	$sVC_{0,35,90\%}$																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH
E_S1	93	96	93	96	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
E_S2	89	94	91	93	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
S_S1	78	86	81	85	83	87	84	86	83	87	84	86	84	87	85	87	83	87	84	86	83	87	84	86	84	87	85	87
S_S2	71	81	74	79	80	84	81	83	80	84	81	83	82	85	82	84	79	84	81	83	80	84	81	83	82	86	82	84

Figure 8 – Spatial Visual Comfort Availability (%) for East and South orientations in the different configurations analyzed (symbols are explained in Table 1).

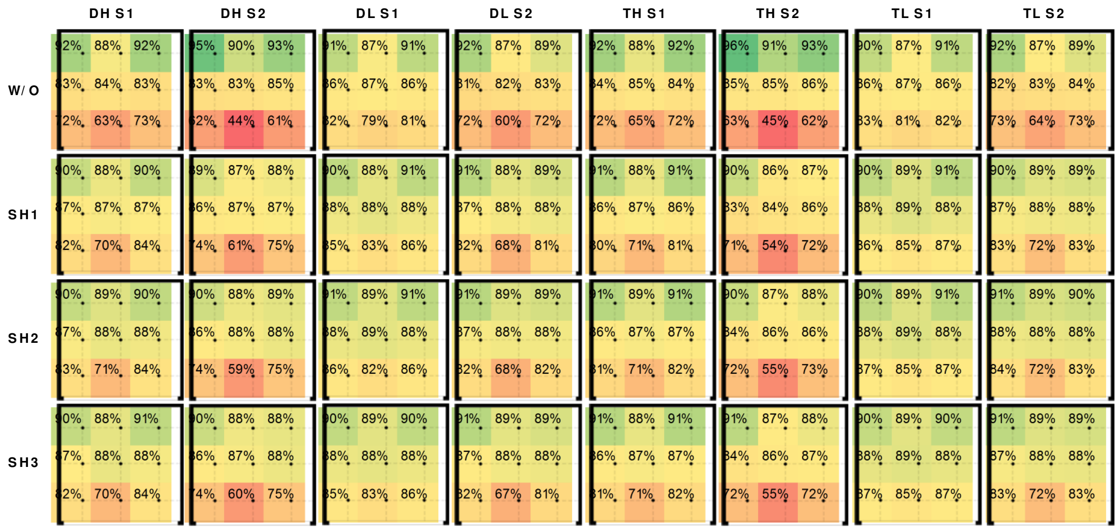

Figure 9 – Thermal Comfort Availability distribution for South orientation and external shades. Each square represents the plant of the office with the window on the South side (symbols are explained in Table 1).

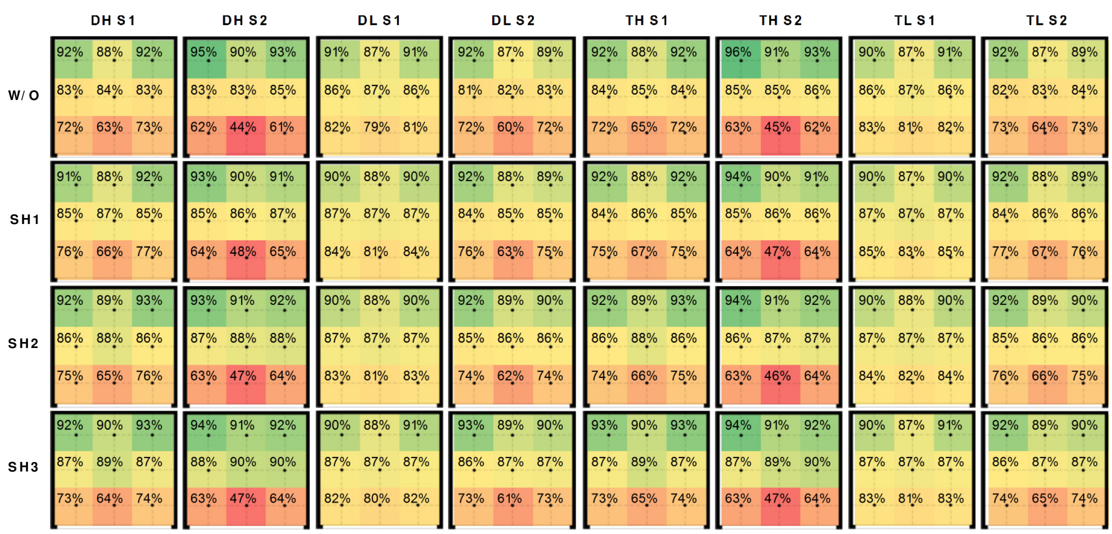

Figure 10 – Thermal Comfort Availability distribution for South orientation and internal shades. Each square represents the plant of the office with the window on the South side (symbols are explained in Table 1).

Configuration	$sTC_{10,90\%}$ - IRRADIATED																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH	DH	DL	TL	TH
E_S1	11	67	11	67	89	100	89	100	100	100	89	100	89	100	89	100	11	44	11	22	11	22	11	22	22	67	22	22
E_S2	0	22	11	22	67	89	22	89	67	89	67	89	67	89	56	89	22	33	22	22	22	22	22	22	22	22	22	22
S_S1	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	11	22	11	22	22	22	11	22	22	22	22
S_S2	22	11	33	11	0	11	11	11	0	11	11	11	0	11	11	11	22	11	22	11	33	22	33	22	33	22	33	22

Figure 11 – Spatial Thermal Comfort Availability (%) for East and South orientations in the different configurations analyzed (symbols are explained in Table 1).

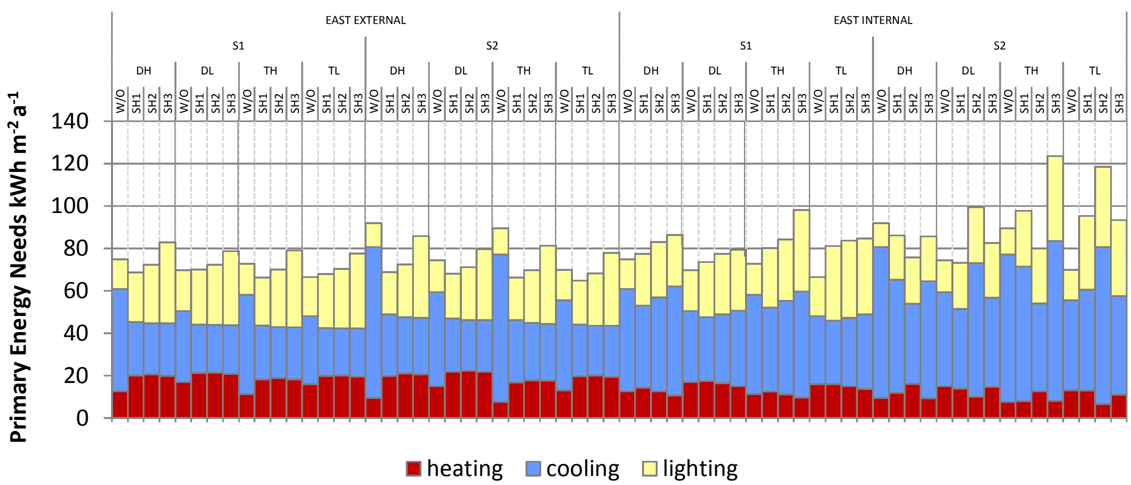

Figure 12 – Primary energy needs in the different configurations for East orientation.

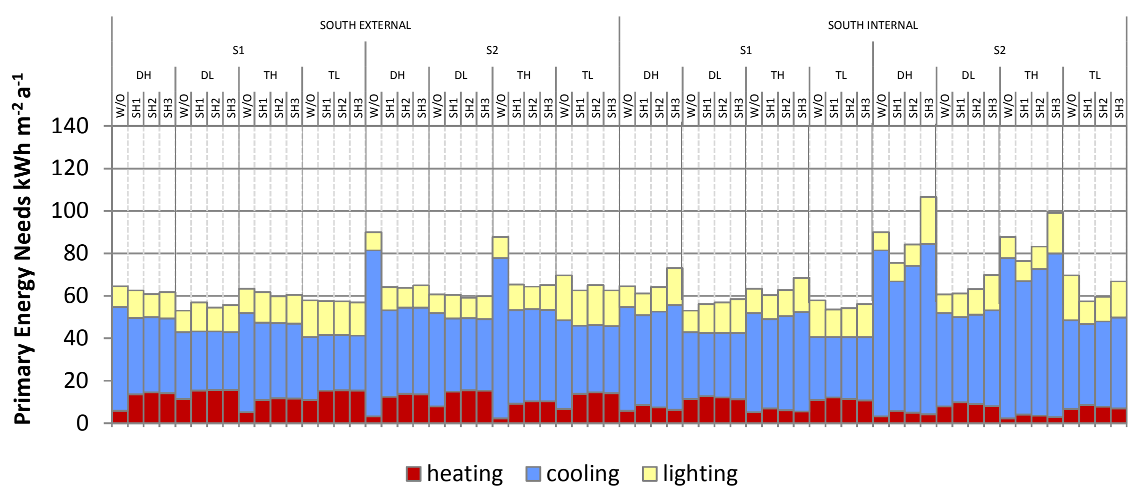

Figure 13 – Primary energy needs in the different configurations for South orientation.

Orientation	EAST												SOUTH											
Glazing	DH			DL			TH			TL			DH			DL			TH			TL		
Shading SH	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
S1 Ext	-	-	+	-	-	+	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
S1 Int	+	+	+	-	+	+	+	+	+	+	+	+	-	-	+	-	-	-	-	-	+	-	-	-
S2 Ext	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S2 Int	-	-	-	-	+	-	+	-	+	+	+	+	-	-	+	-	-	-	-	-	+	-	-	-

Figure 14 – Synthetical overview of the energy performance of the window system (glazing and shades) in terms of increase (in red) or reduction (in green) of primary energy needs with respect to the corrisponding case without shades.