On the Global Performance of Offices with Different Complex Fenestration Systems

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Abstract

Complex fenestration systems influence indoor comfort conditions and energy consumption in a complex way. If all the involved aspects are not considered jointly since the design phase, buildings can show a deep gap between their planned and real performance, especially when dealing with low energy buildings (Vanhoutteghem et al., 2015). This can be avoided by identifying the design configurations able to provide a trade-off between contrasting requisites: improving comfort conditions while minimizing energy use. This work analyzes and compares different design solutions for an open space office from a global performance perspective. Dependence on the building characteristics and operation strategy has been assessed by comparing two different windows sizes, three glazing systems, and three different approaches to control the shading devices, for a South oriented façade in the climate of Rome. The study has been conducted combining a RADIANCE/DAYSIM lighting simulation with EnergyPlus for the thermal comfort and energy analysis. A set of metrics, able to express both the time constancy and the spatial uniformity of visual and thermal comfort conditions, has been evaluated together with the energy demand for heating, cooling, and lighting. The results show how a global approach allows obtaining a more comprehensive building performance evaluation and, consequently, identifying design solutions capable of enhancing both energy efficiency and occupant comfort.

1. Introduction

Fenestrations with shading devices, or Complex Fenestration Systems (CFSs), due to their thermal and optical complexity can influence indoor visual and thermal conditions, daylight availability and energy consumption in a complicated way. Failure to consider since the early design phase all the concurrent performance aspects, including comfort conditions, which affect occupants' interactions with the building, is one of the causes for the gap between planned and real performance, especially in low energy buildings.

Even if it is possible to identify different approaches for describing thermal and visual comfort conditions and energy use, a common thread can be unveiled in the recent scientific literature: the need to define an optimal trade-off between energy efficiency and indoor well-being. All the studies clearly underline the importance of considering both energy and comfort performance, when designing a building or a façade component.

The evaluation of the global building performance has been conducted by analyzing energy consumption and indoor comfort conditions in Ferrara et al. (2015), Liu et al. (2015), Mainini et al. (2015), Roetzel et al. (2014), Yao (2014a), David et al. (2011).

In Zhang et al. (2017), a Pareto front representation on a 3D space allows to recognize the non-dominated solution in terms of thermal, visual comfort, and energy consumption for heating and lighting.

Vanhoutteghem et al. (2015) used a contour plot representation of the space heating demand imposing three fixed parameters (U-value, windows orientation and room width-to-depth ratio), and plotting the results for different g-values and glazing-to-floor ratio. Thermal and visual comfort are evaluated defining specific boundaries for overheating occurrences and daylighting availability.

Regardless of the indices used for evaluating the building performance, or the software employed for calculating them, there is the need of synthesizing hourly profiles calculated for some specific points in

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the building, and derive zonal and long-term metrics. In Atzeri et al. (2016a), a set of zonal and long-term metrics has been proposed with this aim. Time constancy or spatial uniformity of the considered comfort aspects are at the base of their definition.

In this work, daylight, visual and thermal comfort and global energy consumption for heating cooling and lighting performance have been analysed for a set of 18 open space office building modules in the climate of Rome.

They have been derived from the same reference module, modifying glazing systems, windows size, and control strategies for the shading devices, according to a full factorial plan. The metrics and representations introduced by Atzeri et al. (2016b) have been used to contrast the performances of different CFSs and their operation strategy.

2. Simulation Method and Metrics Calculation

In order to calculate energy and comfort performance of the analyzed building configurations, different simulation codes have been combined. The building model has been developed through Rhinoceros, a commercial 3D computer graphics and computer-aided design (CAD) application software. Grasshopper, a graphical algorithm editor tightly integrated with Rhinoceros 3D modelling tools, has been used for the parametric definition of the different configurations. Daylight, glare, and electric lighting annual profiles have been calculated in a RADIANCE/DAYSIM based lighting simulation software (Roudsari et al., 2013) and then they have been post-processed through MatLab to obtain artificial lighting and roller shades operation schedules useful for energy and thermal comfort simulations with EnergyPlus and to calculate daylighting, visual, and thermal comfort metrics. Indoor visual comfort conditions have been assessed by means of the enhanced Daylight Glare Probability simplified ($eDGP_s$) index, calculated on an annual basis according to Wienold (2009):

$$eDGP_s = c_1 \cdot E_v + c_2 \cdot log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right)\right] + c_3 \qquad (1)$$

Thermal comfort conditions have been assessed by means of the Predicted Mean Vote according to EN ISO 7730:2005 but using a modified Mean Radiant Temperature (MRT) that takes into account the direct and diffuse solar radiation passing through the transparent surfaces and striking the occupants, according to La Gennusa et al. (2005; 2007):

$$MRT_{irr}^4 = \sum_{i=1}^{n} F_{s\to j} I_{d,j}^{in} + \frac{\alpha_{irr,b}}{\varepsilon\sigma} f_p I_{bn}^{in} \qquad (2)$$

For all the RADIANCE based simulations, the ambient bounce (-ab) parameter has been set to 5, in order to be able to consider even the inter-reflection influence deeper in the room.

The natural light distribution has been obtained on a grid of 81 points located 0.8 m above the floor and excluding a peripheral band 0.5 m deep along the walls, even if the results are averaged for being represented for 9 positions to be consistent with the comfort analysis. Thermal and visual comfort indices have been calculated on a grid of 9 points. Thermal comfort points are 0.6 m above the floor, corresponding to the height of a sitting person's stomach. Instead, 1.2 m has been chosen for visual comfort analysis, as the reference height for the line of sight for a sitting person in studies dealing with visual comfort, suggested by several regulations.

The annual energy demand for heating, cooling, and lighting have been calculated by means of EnergyPlus and expressed in terms of primary energy per unit of surface. The simulation has been performed with an hourly time step.

All the other simulation settings (observers' view direction, HVAC, and artificial lighting system characteristics) have already been described in more detail in Atzeri et al. (2016b).

3. Model Setup

Being used especially during daytime, offices are characterized by an even more urgent necessity of balancing thermal and visual comfort requisites, in order to be able, for example, to maximize as much as possible solar gains and daylight contributions, avoiding high cooling demand, glare, and thermal discomfort. These aspects make them an ideal target for this study.

An open space office located in Rome, Italy (Lat. N 42° 54′ 39′′ HDD18: 1420 K d - CDD18: 827 K d) has been chosen for the analysis. Hourly weather data for one year have been used as climatic inputs (US DOE, 2009).

The workspace floor area is 100 m² and the internal height is 3 m. The opaque envelope is made of an internal clay block layer, 0.2 cm thick, and an external insulation layer, 0.12 m thick, with a thermal transmittance of 0.26 W m^{-2} K^{-1} complying with the requisites of the national legislation for the considered climatic conditions. The entire envelope disperses to the outdoor environment, except the floor, which is in contact with a conditioned space, and is considered adiabatic. To model the interaction between light and the room surfaces, walls and ceiling, have been assumed with a reflectance of 70 %, the floor 30 % and the ground 20 %. Different design configurations have been analysed, combining two values for the window dimensions and three glazing types. Roller shades have been chosen due to their widespread availability, especially in buildings belonging to the tertiary sector. Table 1 shows the configuration parameters used, together with the labelling key to represent the different cases in the following.

The optical and solar properties of the roller shades, characterized by a nominal solar and visual transmittance of 0.05, were determined through angular measurements, and calibrated using a validated model (Atzeri et al., 2016b).

Table 1 – Design configuration parameters

Parameters	Values	Labels
Window Wall Ratio (WWR)	45 %	S1
	75 %	S2
Glazing Systems (GS)	1) U_{gl} = 1.1 W m^{-2} K^{-1}; τ_{vis} = 0.77; SHGC = 0.62;	HH
	2) U_{gl} = 1.1 W m^{-2} K^{-1}; τ_{vis} = 0.72; SHGC = 0.36;	HL
	3) U_{gl} = 1.1 W m^{-2} K^{-1}; τ_{vis} = 0.33; SHGC = 0.33;	LL

3.1 Roller Shades Control Strategies

Several researchers underlined that shading devices can lead to a reduction of the building cooling energy needs together with an increase of the indoor environmental quality, related to thermal and visual comfort. Regardless of the physical properties that characterize the fabric material, the possibility to change progressively the shades position can facilitate the balance between solar and glare protection, daylight availability and external view. Even if shades can be operated directly by the occupants, different studies underlined that the manual operation tends to show some hysteresis. Once completely closed, the shades tend to remain in this state for a long period (Konstantoglou and Tsangrassoulis, 2016). The possibility to control them automatically is essential, in particular to avoid the gap between the planned and the real performance of buildings. Different configurations and control approaches have been proposed and analysed in literature. Kapsis et al. (2010) proposed a motorized roller shade that opens from top to bottom. In this way, the roller shade covers the bottom part of the window, while allowing daylight to enter from the top part of the window, thus ensuring uniform light distribution. Two algorithms, aiming at maximizing solar heat gains while reducing heat losses during the heating season, have been suggested by Bastien and Athienitis (2012). One, called *global solar control*, operates the shades based on the global horizontal radiation level, independently of the shades orientation. The other, defined as *individual solar control*, allows controlling shades with different orientations using their respective incident solar radiation level. Both the controls consider only an open-closed shades position. An open-closed operation is also described in Shen and Tzempelikos (2012), where the shades are automatically closed when incident beam radiation on the facade is higher than 20 W m^{-2} and outside work hours. The same authors (Shen and Tzempelikos, 2014) defined a control based on the effective daylight transmitted into the space, used also in Konstantzos et al. (2015). The effective daylight control has been compared to a work plane protection control, where the shading position is a function of the solar profile angle and the distance between the occupant and the window, and to a fully closed state of the shades. Also, in Singh et al. (2015) an open-closed control mode has been used, closing the shade when the glare threshold is exceeded. Xiong and Tzempelikos (2016) considered 11 possible shades positions, choosing the more convenient as the highest that is able to maximize daylight while maintaining visual comfort.

Three visual comfort criteria have been used, respectively based on DGP, vertical illuminance (E_v) and effective illuminance. If all shading positions fail to pass the criterion, the shades are left closed.

In this study, three different approaches to control the roller shades have been considered:

1. Open-closed operation (CTRL1 in the following)

The shades state is determined according to the illuminance level measured on the workplane position closest to the transparent surface: 500 lx is the opening threshold and represents the desired work plane illuminance; 2000 lx is considered the limit value to avoid visual discomfort (Nabil and Mardaljevic, 2006). The shades state depends also on their state in the previous time step: if the shades were already closed and in the current the workplane illuminance is still larger than 500 lx, the shades will be kept closed.

The two next controls are based on the certainty that to ensure a comfortable visual environment it is not necessary for shades to operate in an open/closed mode. On the contrary, they can move to intermediate positions that depend on solar position, sky conditions, and solar penetration depth relative to the occupant position.

2. Solar adaptive operation (CTRL2)

The shade height (h_{sh}) with respect to the work plane height is calculated as:

$$h_{sh} = D \cdot \tan(\Omega) \qquad (3)$$

where D is the distance of the working plane from the facade, and Ω is the solar profile angle (function of solar altitude α and surface solar azimuth γ).

This control method (Tzempelikos and Shen, 2013) allows preventing direct sunlight from falling on the work plane area but can cause glare and overheating problems especially in summer. Moreover, when French windows are considered, this control does not allow closing completely the shades, due to the reference height used in the equation. At the same time, it is very simple to implement, because a pre-calculated schedule can be applied according to the specific building location.

3. Effective daylight operation (CTRL3)

The effective illuminance E_{ff} (Shen and Tzempelikos, 2014) represents the overall illuminance transmitted through the window, measured on the same plane, considering both the shaded (E_{sh}) and unshaded (E_g) parts of the window:

$$E_{eff} = \frac{\sum_i (E_{gi} \times A_{gi} + E_{shi} \times A_{shi})}{\sum_i (A_{gi} + A_{shi})} \qquad (4)$$

Once fixed a reference value for the work plane illuminance, it is possible to determine a limit value for E_{ff} that represents a threshold, called E_{esp}, analyzing the correlation between the two quantities in the case of CTRL2. Using this threshold, a new equation to calculate the shades height can be defined:

$$h_{sh} = \frac{(E_{esp} - E_{sh}) \cdot H}{E_g - E_{sh}} \qquad (5)$$

Where H represents the total window height. Then, the final shades height can be iteratively chosen as the smaller value between those calculated using Equations (1) and (3):

$$h_{sh} = \min\left\{D \cdot \tan\Omega, \frac{(E_{esp} - E_{sh}) \cdot H}{E_g - E_{sh}}\right\} \qquad (6)$$

All the three controls close the shades completely during the unoccupied hours.

4. Results and Discussion

Results will be represented and discussed by means of the zonal and long-term performance metrics as described in Atzeri et al. (2016b), namely availability, spatial availability, usability, time, and through the energy demand for heating, cooling, and lighting. Since the performance depends on the shade operation, Fig. 1 compares the shades position obtained by applying the three different controls previously described. For space reasons, only the small windows equipped with HH glazing systems have been considered. The yellow color ramp allows recognizing the shades opening percentage from 0 (black) to 100 % (white).

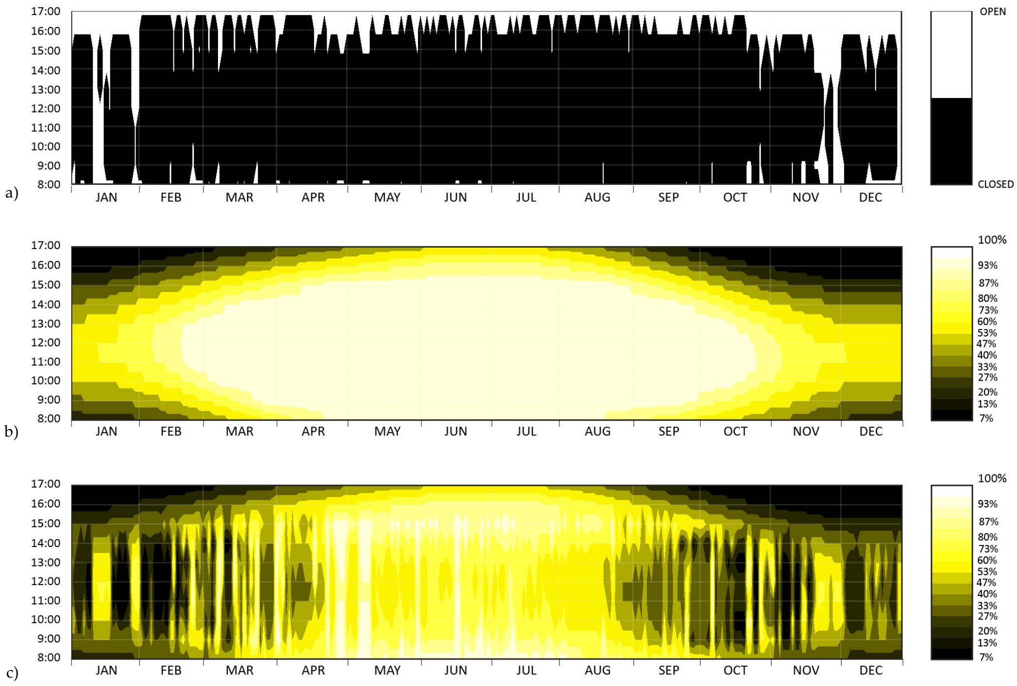

Fig. 1 – Temporal plot for the shades' opening percentage according to CTRL1 (a), 2 (b) and 3 (c) for the small window S1, with HH glazing system

Fig. 2 allows the comparison of the shades operation according to the three control strategies for all the glazing systems. The yellow columns represent the number of hours during which shades are open, the black ones the number of hours with closed shades, and the grey ones the number of hours when shades are in an intermediate position (only for CTRL2 and 3). With the exception of CTRL2, which considers only the sun position to manage the shades, the shades position frequency changes with the control strategy and with the type of glazing.

Tables 2 and 3 point out for how long, considering CTRL2 and CTRL3, the roller shades remain at a certain distance from the windowsill. The duration is expressed as time percentage compared to the annual occupation hours. In particular, looking at Table 3 it can be noticed that, since the reference height of the working plane is 0.8 m, with CTRL2 the shades cannot assume a distance from the windowsill lower than 0.8 m.

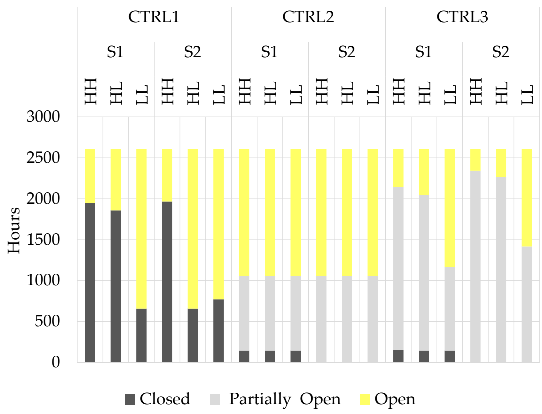

Fig. 2 – Shades opening state during occupancy period according to the control strategy for the different glazing systems

On the contrary, when the CTRL3 equation is used, the shades can overcome this limit to reduce excessive workplane illuminance and with some impact on possible overheating and discomfort conditions, as underlined in the following.

Table 2 – Shades position in small windows S1: percentage of occupancy period for different heights from windowsill

Height (m)	CTRL2			CTRL3		
	HH	HL	LL	HH	HL	LL
1.5	60	60	60	18	22	55
1.4	2	2	2	4	3	2
1.3	2	2	2	3	4	2
1.2	2	2	2	4	6	3
1.1	2	2	2	6	7	3
1	3	3	3	7	6	2
0.9	3	3	3	7	6	4
0.8	4	4	4	7	6	5
0.7	6	6	6	7	7	7
0.6	3	3	3	8	7	3
0.5	3	3	3	6	6	3
0.4	1	1	1	4	5	1
0.3	2	2	2	5	5	2
0.2	1	1	1	5	4	1
0.1	0	0	0	3	2	0
0	6	6	6	6	6	6

Table 3 – Shades position in large windows S2: percentage of occupancy period for different heights from windowsill

Height (m)	CTRL2			CTRL3		
	HH	HL	LL	HH	HL	LL
2.5	60	60	60	10	13	46
2.4	2	2	2	2	1	2
2.3	2	2	2	2	1	2
2.2	2	2	2	1	3	3
2.1	2	2	2	2	2	3
2	3	3	3	3	3	2
1.9	3	3	3	4	3	4
1.8	4	4	4	4	3	4
1.7	6	6	6	4	4	5
1.6	3	3	3	3	4	4
1.5	3	3	3	5	5	4
1.4	1	1	1	4	5	3
1.3	2	2	2	6	6	4
1.2	1	1	1	6	5	3
1.1	0	0	0	4	4	1
1	1	1	1	5	4	2
0.9	1	1	1	5	5	2
0.8	4	4	4	9	9	6
0.7	0	0	0	5	4	1
0.6	0	0	0	4	3	0
0.5	0	0	0	2	2	0
0.4	0	0	0	2	2	0
0.3	0	0	0	3	3	0
0.2	0	0	0	3	3	0
0.1	0	0	0	3	1	0
0	0	0	0	0	0	0

4.1 Daylighting Performance

Table 4 shows the spatial distribution of Daylight Autonomy, DA_{500} through the office, for all the design configurations and the three shading controls proposed.

Starting with S1 cases, with CTRL1, DA_{500} is insufficient regardless of the position analyzed, and, comparing the three glazings, only LL guarantees a slight sufficient DA in the first row close to the windows.

As expected, with CTRL2, DA values and distribution improve for all the glazings. HH and HL have the best performance in all the positions and with HH the highest DA is obtained in the third row. With LL the DA distribution is similar to the one obtained with CTRL1, even if in this case useful values can be reached at least in the row close to the window.

With CTRL3, again HH and HL guarantee the best performance, even if the DA distribution is less homogeneous. With glazing LL, DA is acceptable only in the first row and useless in the second and third rows. Compared to CTRL2, the values of DA in the first row are almost the same, in the second almost half, and, in the third row, the situation is as negative as with CTRL1.

Cases with windows S2 have the same trend as cases S1, but the large windows allow higher DA in the second rows in almost all the cases and controls.

Table 5 shows the spatial Daylight Autonomy, sDA, for the three controls, the three glazings and the two window areas: with CTRL1, glazings HH and HL have sDA null, while glazing LL guarantees an sDA of 33 % that coincides with the first row from the window. With CTRL2, glazings HH and HL perform in the same way and guarantees 67 % sDA, that means the acceptable DA in the first two rows, while glazing LL guarantees adequate DA only in the first row. Finally, with CTRL3, adequate DA is guaranteed only in the first row with all the three glazings. The situation is very similar with large windows even though with CTRL2 100 % sDA is reached using HH and HL glazings. Concluding CTRL2 allows obtaining the best performance in terms of daylight availability, regardless of the window dimensions and with all the glazing types.

Concerning the usability of the space, in terms of the fraction of space with a sufficient daylighting level, e.g. 500 lx, in the same moment, Fig. 3 shows the percentage of the occupancy time for different values of Daylight Usability. The control that guarantees the higher DU is CTRL2 with HH and HL glazing: with small windows, DU is 90 % for the 22 % of the time with HH and 13 % of the time with HL glazing, and it is about 50 % for large windows, with both HH and HL glazing. Nevertheless CTRL3 always perform better than CTRL1. These quantities represented by a red solid line in the figure, are the time Daylight Usability (tDU), summarized in Table 5. The threshold of 90 % of Daylight usability is never reached by the other cases with both S1 and S2.

4.2 Visual Comfort

The VCA distribution (Table 4), underlines that for almost all the glazing systems, regardless the control approach, the window dimension and the occupant's position, are able to ensure a comfortable environment from a visual point of view.

The only design configurations that are not able to fulfil the required environmental conditions, are those coupling CTRL2 with HH and HL glazing systems, for the left and central points on the first row. Particularly critical are the values related to the larger windows, where the DGP lies above 0.35 for more or less half of the occupancy time. sVCA values in Table 5, confirm what has been previously pointed out.

When applying CTRL2 to HH or HL glazing systems, the fraction of space in the room in visual comfort conditions for at least 90 % of the reference period lies always under the threshold selected. The most critical condition is associated to the largest windows equipped with HH glazing; where DGP is lower than 0.35 only for 66 % of the room.

When VCU is considered (Fig. 3), HH and HL glazings coupled with CTRL2 show a reduced fraction of space simultaneously in visual comfort with respect to CTRL1 and 2.

4.3 Thermal Comfort

Thermal comfort availability is very high (higher than 90 %) in all the points in the space for almost all the cases (Table 4). In particular, CTRL1 ensure a good homogeneity with HH and HL glazings, while with LL, TCA falls between 80 % and 90 % in the row close to the windows and in the middle point in particular. The performance with CTRL3 is similar: TCA is very homogeneous in the space and only the position in the middle of the first row has a TCA between 80 % and 90 %. CTRL2 assures higher TCA than the other controls in the rows far from windows, while in the points closer to the windows TCA is particularly low (57 %) in the point in the middle of the first row, close to the window. Consequently, it is possible to see that Spatial Thermal Comfort Availability, sTCA, is 100 % with CTRL1 and glazing HH and LL, with both large and small windows, and with CTRL3 is 100 % with HH and HL but only for small windows. With glazing HH and HL, CTRL1 and CTRL3 are the best controls for small windows, while CTRL1 is the best for large windows. With glazing LL the three controls perform in the same way guaranteeing 89 % of sTCA in cases with small windows and 67 % with large windows.

Concerning the contemporaneity of the comfort achievement over the space, Table 5 reports time Thermal Comfort Usability: CTRL1 guarantees 90 % of usability for about the 90 % of the time with HH and HL glazings, with both large and small windows, while the percentage decreases with LL glazing (87 % with small windows and 76% with large windows). CTRL2 gives the worst results in terms of time usability especially with HH glazing, while CTRL3 gives intermediate results: with small windows the performance is better than with large windows and HL glazing performs better than HH and LL glazings.

4.4 Energy Consumption

A previous work (Atzeri et al., 2014) underlined how the use of shading devices can affect the energy performance in different ways, depending on their optical properties and position, on windows orientation and size. In this study, the analysis has been concentrated mainly on the effect of different shades controls, pointing out their possible influence in terms of energy consumption. The primary energy demand for heating, cooling, and artificial lighting is plotted in Fig. 4 for all the cases investigated.

Generally, CTRL2 and CTRL3 give the best results in terms of artificial light demand, reducing considerably energy consumption compared to CTRL1. When the shades position mainly depends on the glazing system properties, as it happens for CTRL1, LL glazing systems perform better. Their lower visual transmittance allows shades to stay open for longer period than with other glazing, maximizing the use of natural light. On the contrary, when

CTRL2 and CTRL3 are considered, the best performance derives from HH and HL. These glazing systems are characterized by a very similar trend across the different design configurations, due to their close visual transmittance. On the contrary, when cooling consumption is considered, different control systems can produce different trends. It happens especially using CTRL2. It determines a longer shades opening period along the year and, when it is applied to the larger windows, it does not allow the shades to be less than 0.80 m from the bottom edge of the windows, thus increasing solar gains. The same behavior can be pointed out considering CTRL3 results, but in this case, the difference between HH and HL glazing systems is less evident. HH and HL, except for CTRL2 applied to large windows for the reason described above, perform better than LL for the cooling aspects.

Actually, when a control system based on illuminance values, is applied, glazing systems allow a bigger amount of natural light entering the confined environment, together with the solar radiation. It can be particularly critic when a climatic location, as Rome, where cooling demands represent the main source of energy consumption, is considered.

Concerning the total energy demand, HL glazing systems, coupled with CTRL3, provide the best performance, reducing simultaneously both artificial lighting and cooling demand.

Table 4 – DA_{500}, VCA_{35} e TCA_{10} for small and large windows. Tables represents the room plan, the thick border the walls, and the missing border the window position

		CTRL 1			CTRL 2			CTRL 3		
		HH	HL	LL	HH	HL	LL	HH	HL	LL
DA	S S1	0 0 0	0 0 0	0 0 0	25 31 26	16 24 18	0 0 0	0 0 0	0 0 0	0 0 0
		1 1 2	2 3 3	3 4 3	62 67 66	63 66 64	10 14 11	38 47 40	42 48 39	4 8 6
		16 17 17	19 20 20	53 58 56	84 86 85	83 85 84	70 75 73	83 86 85	82 85 84	70 75 73
	S S2	0 0 0	0 0 0	0 0 0	54 55 52	52 53 51	0 1 1	0 0 0	0 0 0	0 0 0
		2 5 3	3 5 3	12 17 13	72 76 74	72 74 71	31 39 31	37 47 38	36 44 35	14 22 13
		14 16 15	15 17 16	51 56 54	88 88 88	87 88 87	74 78 77	87 88 86	86 88 87	74 78 77
VCA	S S1	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100
		100 100 100	99 100 100	99 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100
		99 99 100	99 99 100	97 98 100	74 76 94	78 82 96	99 99 100	98 99 100	98 99 100	99 99 100
	S S2	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100
		100 100 100	100 100 100	99 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100	100 100 100
		99 99 100	99 99 100	98 98 100	48 50 77	53 55 82	99 99 100	99 100 100	99 100 100	99 99 100
TCA	S S1	91 92 91	91 92 91	92 92 92	95 93 95	93 93 93	93 93 93	92 92 92	92 92 92	93 93 93
		91 91 91	92 91 92	92 92 92	93 93 93	93 93 93	93 93 93	92 92 92	92 92 92	93 93 93
		91 91 91	91 91 91	92 88 92	89 76 89	92 88 92	93 89 93	92 90 92	92 91 92	93 89 93
	S S2	91 92 92	92 92 92	92 92 92	95 93 94	94 94 94	94 93 93	92 92 92	92 92 92	93 93 93
		92 92 92	92 92 92	92 92 92	92 92 92	93 93 93	93 93 93	92 92 92	92 92 92	93 93 93
		91 90 91	92 91 92	88 78 87	73 57 73	87 73 86	87 73 87	89 87 89	91 89 91	89 81 89

Table 5 - Spatial Availability and Time Usability for small and large windows

		Spatial Availability									Time Usability								
		CTRL1			CTRL2			CTRL3			CTRL1			CTRL2			CTRL3		
		HH	HL	LL	HH	HL	LL	HH	HL	LL	HH	HL	LL	HH	HL	LL	HH	HL	LL
D	S S1	0	0	33	67	67	33	33	33	33	0	0	0	23	17	0	0	0	0
	S S2	0	0	33	100	100	33	33	33	33	0	0	0	53	49	0	0	0	0
VC	S S1	100	100	100	78	78	100	100	100	100	99	99	97	72	77	99	98	98	99
	S S2	100	100	100	67	67	100	100	100	100	99	99	98	46	51	99	99	99	99
TC	S S1	100	100	89	67	89	89	100	100	89	90	90	87	75	86	87	89	90	88
	S S2	100	100	67	67	67	67	67	89	67	89	90	76	56	71	71	85	87	79

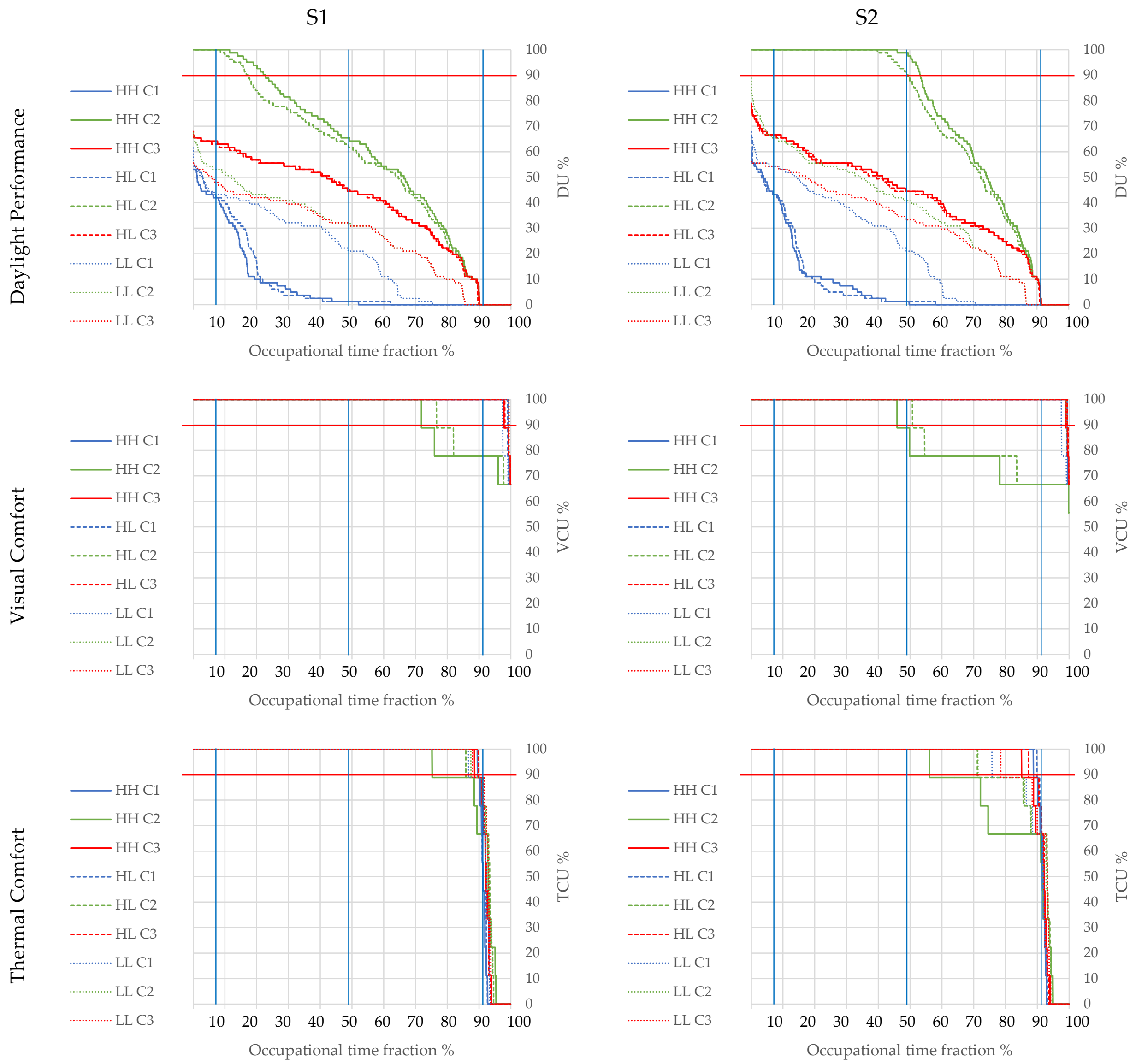

Fig. 3 – Daylight Usability, Visual Comfort Usability, and Thermal Comfort Usability for small and large windows

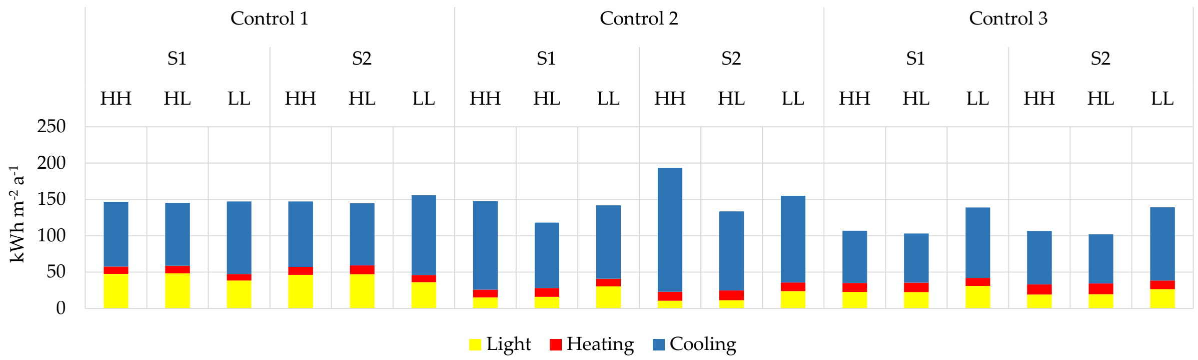

Fig. 4 – Primary Energy demand for artificial lighting, heating and cooling

5. Conclusion

In this paper, the integrated performance of different CFSs coupled with three control approaches for shading devices is presented. The first is characterized by a standard open-closed operation, while the others are able to assume intermediate positions according to solar position and effective daylight. The building's *global* performance has been assessed, considering thermal and visual comfort conditions and daylighting availability besides overall energy demand. Results have been expressed in terms of availability, spatial availability, usability, time usability (Atzeri et al., 2016b), and energy demand for heating, cooling, and lighting.

Outcomes underline that advanced controls for shades operation, not working with an on-off mode, are able to ensure a suitable indoor environment and to reduce energy consumption. However, performance obtained with advanced controls is more affected by the type of glazing system adopted which determines different amounts of energy demand. Furthermore, it has been demonstrated that CTRL3 guarantees a more homogeneous distribution of the natural light, even in a deep space as the one used in this study.

Concerning CTRL2, as already underlined in Tzempelikos and Shen (2013), the results confirm that, although this operation mode is very simple to apply, it is not able to ensure the same comfort performance, in terms of visual and thermal quality, nor the same energy demand, as CTRL1 and CTRL3. Beyond the previous advantages, the possibility to locate the shades on intermediate positions can help the occupants to maintain a closer connection to the outdoor environment, improving their perception of the confined space.

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