Long-term and spatial evaluation of the integrated performance of a window-shade system in an open space office located in Rome

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Abstract

The building façades, as a boundary between external and internal environments, play a central role in energy reduction and suitable comfort conditions maintenance. Their evaluation requires an integrated assessment approach, focused on occupants' thermal and visual comfort, in time and space, as well as on maximizing daylight and achieving energy saving goals. In this paper, dynamic simulation is used to evaluate the integrated performance of different fenestration systems in an open space office located in Rome. The illuminating analysis has been performed using DIVA, and the results, processed by means of a Matlab code, have been used as an input for Energy Plus thermal and energy analysis. Then, the Energy Plus outputs have been post processed to calculate the solar radiation influence on occupants thermal comfort. Some new metrics have been introduced in such a way that it is possible to assess the comfort performance with comprehensive indicators.

1. Introduction

The quantity of energy used to operate a building often depends on the comfort level perceived by the occupants (Nielsen et al., 2011). There are different physical elements which can influence the occupants' comfort perception. Some of those have been analysed and their effects can be easily represented. Others, like the transient solar radiation effects, have had less exposition due to the complexity of solar radiation behaviour. At the same time, the modern buildings are characterized, especially the offices, by a more and more intensive use of glazing surfaces. The transparent components of the envelope can have both positive and negative effects, often contrasting, on the comfort conditions and on the energy needs. At the moment there are few examples of comprehensive studies which analyse both the overall energy demand (heating, cooling and lighting), and comfort conditions (thermal and visual). In most of the cases the metrics used to assess the thermal comfort do not consider the effect of solar radiation on the occupants' perception and often the space distribution of comfort is neglected. Moreover, the building's comfort performance assessed by means of comprehensive metrics, able to consider both long-term and spatial distribution, is rarely discussed.

This paper puts together all these aspects, considering the effects of different windows' glazing systems and shading devices, both on thermal and visual comfort and on overall building energy demand for an open space office located in Rome. The shades are managed in order to avoid or to reduce the visual discomfort and overheating conditions. The lighting system and shading devices work together to ensure a suitable illuminance level on the work-plane. The influence of the control setting on the energy performance has been evaluated calculating the overall primary energy demand, while the capacity in maximizing the natural light use has been assessed through the illuminance values. The analysis of the long-term comfort conditions has been conducted on a seasonal basis, taking into account both the thermal and visual comfort. The visual comfort has been assessed calculating the Daylight Glare Probability (DGP) in 9 different positions in the office, while the thermal comfort has been evaluated considering the Predicted Percent of Dissatisfied, including also the effect of the diffuse and beam solar radiation directly reaching the occupants (Cappelletti et al., 2014). Using Daylight Glare Probability (DGP) and People Percentage of Dissatisfied (PPD) two comprehensive metrics have been calculated to assess the long-term and spatial comfort performance.

2. Modelling Methodology

Previous studies (Ramos & Ghisi, 2010) pointed out that Energy Plus is not able to simulate precisely the real indoor lighting conditions, since its algorithm cannot solve the internal reflectance properly as well as calculate exactly the external horizontal illuminance. This causes an overestimation of the interior daylight and an underestimation of the lighting needs. To overcome this problem it is possible to couple Energy Plus with DIVA, which performs a daylight analysis via integration with Radiance and DAYSIM, whose algorithms are well developed and widely validated. DIVA's lighting and shading schedules can be used as input for Energy Plus analysis. This approach works well if we consider a side-lit room. If we analyse a room with windows located on facades and we want to manage the shades according to the illuminance related with their specific orientation, the DAYSIM simulation assumption and simplification makes it impossible. As specified in the user guide, DAYSIM calculates the daylight coefficient and the annual illuminance profiles for the bare case plus each additional shading device state. In our study we supposed one shade state in addition to the bare case, with the shades totally closed. Considering a room with windows on opposite facades, this means that the software should simulate all these combinations:

1. Both shades fully opened;
2. One shade opened and the other closed and vice versa;
3. Both shades fully closed.

Actually, DAYSIM does not calculate all the possible shading combinations; it only makes an estimation of what the illuminance should be with only one shading state closed. This approach removes too much light from one of the two control sensors and keeps the relative shades from triggering due to the assumption the software makes. For this reason, we used DIVA only to obtain the illuminance and DGP profiles for each one of the shading states and we used a MATLAB code to combine them in order to obtain the lighting and shading schedules for Energy Plus and the daylighting metrics. Through the Energy Plus simulation we obtained the overall primary energy needs and a list of outputs which have been post processed through MATLAB to calculate the influence of solar radiation on occupants' thermal sensation and the thermal comfort indicators.

3. Simulation Settings

3.1 Geometrical Model and Parametrical Analysis

The model is an open space office of 100 m^2 of floor area and 3 m of interior height located in Rome - Italy (Lat. N 42° 54′ 39′′; HDD18: 1420 K d - CDD18: 827 K d). The windowed façade has been simulated east oriented. A parametrical analysis has been performed by varying some building envelope characteristics, as summarized in Table 1.

Table 1 – Variables used in the analysis

Building Parameter	**Values**
Glazing	DH Double Glazing high SHGC Ugl = 1.14 W m^{-2} K^{-1}; SHGC = 0.60; τ_{vis} = 0.81 DL Double Glazing low SHGC Ugl = 1.08 W m^{-2} K^{-1}; SHGC = 0.35; τ_{vis} = 0.58 TH Triple Glazing high SHGC Ugl = 0.60 W m^{-2} K^{-1}; SHGC = 0.59; τ_{vis} = 0.73 TL Triple Glazing low SHGC Ugl = 0.61 W m^{-2} K^{-1}; SHGC = 0.35; τ_{vis} = 0.63
WWR	S1: 45%; S2: 75%
Shading devices (located internally and externally)	W/O: Without shades SH1: High solar transmittance: ρs=0.58; τs=0.16; ρv=0.51; τv=0.15 SH2: Medium solar transmittance: ρs=0.37; τs=0.10; ρv =0.35; τv=0.10 SH3: Low solar transmittance ρs=0.13; τs=0.05; ρv =0.06; τv=0.05

3.2 Characteristics of Components - Energy Plus and DIVA

Regarding Energy Plus, the walls and roof have been modelled as external while the floor as an adiabatic surface. The composition of the opaque elements is identical, with 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 walls and the roof (both sides). The wall emissivity is 0.9, internally and externally.

The Radiance simulation parameters have been fixed with the aim of analyzing the effect of the fabric throughout the depth of the office.

Table 2 – Radiance parameters' values

Radiance parameters	**Values**
ambient bounce (ab)	5
ambient division (ad)	1000
ambient sampling	20
ambient resolution	300
ambient accuracy	0.1

All the opaque components have been simulated through the RADIANCE material PLASTIC. Wall and ceiling's reflectance are equal to 0.7, and the floor ones is equal to 0.4, which corresponds to plaster and tiles very light colored. The specularity and the roughness have been set equal to 0. For the glazing systems the material GLASS has been used, converting the glass transmittance in transmissivity at normal incidence. The roller shades have been simulated through the material TRANS, which allows defining beam/diffuse ratio but still does not consider angular differences (Chan et al. 2014). Apian-Bennewitz (2013) pointed out that this function is the most suitable one for modeling roller shades in RADIANCE when BSDF information, or other angular solar optical properties, are not available. A TRANS material is defined through its RGB reflectance, transmissivity and transmitted specular component. Two of the shades simulated, SH1 and SH3, are commercial, produced by Helioscreen. For these it has been possible to obtain the direct and diffused part of the light transmission. The properties of shade SH2 has been calculated by means of analytical regression in order to obtain intermediate characteristics between SH1 and SH3.

3.3 Internal gains

The office is occupied from Monday to Friday from 8:00 a.m. to 6:00 p.m. The occupancy index has been fixed as 0.12 people m^{-2}. The occupants' metabolic heat flux is equal to 70 W m^{-2} (75 W sensible portion, 55 W latent). The clothing unit thermal resistance is 1 clo during the heating season (1st October-31st March), and 0.5 clo during the cooling season (1st April-30th September). The electrical equipment internal loads are equal to 1.31 W m^{-2}, while the Light Power Density is 12 W m^{-2}.

3.4 Controls Setting

The artificial lights have been managed, through a photo-sensor-controlled dimming system, to maintain 500 lux on the work plane area. In order to maximize the contribution of the incoming daylight, a control point for each row of lights parallel to the windows has been chosen. The roller shading control operates in order to avoid excessive daylighting levels inside the confined space considering two possible shade positions, fully opened or fully closed. The shade's position depends on the illuminance values measured by an internal sensor, located on the work plane closest to the transparent surface, which uses 500 and 2000 lux like limit values; 500 lux represents the desired work plane illuminance and 2000 lux is considered as limit value to avoid visual discomfort (Nabil & Mardaljevic, 2006). The shades are also closed during the unoccupied hours for all the year.

The heating and cooling systems functioning depends on two bands for the operative temperature, 20°C to 24°C during the heating season and 23°C to 26°C during the cooling season, to comply with the comfort Category B (normal level of expectation about the conditions of comfort for users). The temperature bands operate on weekdays from Monday to Friday and from 8 a.m. to 6 p.m. A heating setpoint of 15 °C and a cooling setpoint of 38 °C have been considered for the nighttime and weekends. This way, while the heating setpoint is fixed in order to prevent the air temperature becoming too low, the cooling setpoint is fixed in order to guarantee that the system is switched off. To assess the thermal comfort conditions inside the office, a grid consisting of 9 points at 0.8 m from the floor level was considered, while for visual comfort the same points have been considered at 1.1 m from the floor level.

4. Performance metrics

The performance of the simulated environment has been evaluated by means of two different types of indicators. The first type, which has been called *"Extensive - Long-term quantitative performance metrics"*, describes the percentage of annual working hours during which each point belonging to a specified grid is above a specified level. Through this indicator we can obtain a spatial description of the simulated environment.

The second type, called *"Synthetic - Spatial long-term quantitative performance"*, describes the percentage of floor area in which the respect of a specified limit value, for a certain percentage of working hours, is maintained.

4.1 Comfort performance metrics

Both the thermal and visual comfort conditions have been evaluated only during the occupancy period. Regarding the comfort performances, the extensive metrics used express a condition of discomfort, while the synthetics express a positive performance. For the thermal comfort, the metrics used have been created calculating the PPD but, besides the standard index, a corrected PPD (PPD_{irr}) has been evaluated considering the effect of solar radiation that directly reaches the occupant (La Gennusa et al., 2007). In this case the extensive metric has been called *Thermal Discomfort Time* (TDT_{PPD}), and it represents the percentage of annual working hours during which the PPD at a given point in the space overcomes the limit value, 10%, threshold values for B category, according to EN ISO 1251:2008. Otherwise, since the objective of the study is also the evaluation of the office's performance in its entirety, a comprehensive indicator, *Spatial Thermal Comfort* ($\text{sTC}_{10,90\%}$), has been calculated. It represents the percentage of floor area in which the PPD is less than 10% for the 90% of annual working hours considering both the standard and the irradiated index.

The visual comfort has been analyzed by means of the Daylight Glare Probability (Wienold & Christoffersen, 2006), calculated in 9 positions over the space, considering a specified view's direction. The extensive performance has been evaluated by means of the metric called *Visual Discomfort Time* (VDT_{DGP}), which expresses the percentage of annual working hours during which the DGP at a given point in the space overcomes 0.35, which is considered the lower limit of acceptable glare values (Wienold & Christoffersen, 2006). Finally, a comprehensive metric has been calculated to account for the glare's spatial variability, called *spatial Visual Comfort* ($\text{sVC}_{0.35,100\%}$), and it has been defined as the percentage of floor area in which there is never glare discomfort.

4.2 Daylighting and energy performance metrics

As an extensive metric, the percentage of working hours when the daylight illuminance is above 500 lux has been used (*Daylight Autonomy* - DA).

As a synthetic metric to summarize annual daylighting performance throughout the space the *spatial Daylight Autonomy* (sDA) has been calculated. sDA (IES, 2012) provides a measure of daylight illuminance sufficiency for a given area, reporting the percentage of floor area that exceeds a specified illuminance level, 500 lux, for a specified amount of working hours, 50%.

Concerning the energy performance the heating, cooling and lighting energy demands have been evaluated in terms of *Primary Energy* use (PE). As described in Cappelletti et al. (2014), controlling the heating and cooling systems by means of the operative temperature, allows us to interpret the energy demand as a double indicator of the envelope's passive energy and comfort performance. In this way, the energy performance of different cases can be compared under equivalent comfort conditions. Moreover, the control of the operative temperature allows us to ascribe the discomfort only to the inlet solar radiation striking the occupant, thus helping in the assessment of the shading device efficacy. To convert the energy needs in primary energy, we used 0.8 as seasonal energy production efficiency for heating and a seasonal Energy Efficiency Ratio of 3 for cooling. A value of 2.174 of primary energy content per unit of electrical energy has been assumed according to the Italian electrical system. Finally, the synthetic metric related to the energy performance has been built considering the ratio between the energy performance of a specific case with shade and the reference case without shade ($EP_{sh}/_{wo}$).

5. Results

5.1 Indoor thermal comfort

The $sTC_{10,90\%}$ metric calculated with the standard index (Fig. 2) highlights a thermal environment able to stay within the chosen limit, except for the internal shades. When we consider the contribution of the solar radiation (Fig. 1), with the small windows coupled with the external shades, we are always able to ensure the right thermal comfort conditions, but the unshaded configurations and the internal shades can respect the threshold only using the low SHGC glazing. With the biggest windows, the comfort conditions requested can be reached only through the TL glazing coupled with the external shades. The TDT_{PPD} index (Fig. 5) highlights the distribution of the thermal discomfort sensation through the space. In this case, if we analyze the results correlated with the standard index, the thermal environment keeps homogenous, regardless of the shade's presence. The irradiated TDT_{PPD}, instead, shows how and how much the thermal discomfort arises as we consider the positions closest to the transparent surfaces. Moreover, whereas the shade SH3, located externally, can reduce the thermal discomfort time up to 60% compared to unshaded configuration, the same shade located internally is not able to reduce the TDT_{PPD} more than 35%.

5.2 Indoor visual comfort and daylighting performance

For visual comfort and daylighting performance, we obtain very similar results regardless of the shade's position. The use of the roller shading system leads, globally, to a decrease of the $sDA_{500,50\%}$ (Fig. 3) for both the window's size and the DA_{500} (Fig. 6) decreases faster distancing from the transparent surfaces. The view's direction used for the simulation makes sure that even the unshaded combinations remain close to the limit chosen for the $sVC_{0.35,100\%}$ (Fig. 4), but only thanks to the shades can we ensure the visual comfort for all the positions analyzed. If we analyze the visual discomfort locally (Fig. 7), with the bare windows the points closest to the biggest windows can stay under discomfort conditions up to 29% of the annual working hours.

5.3 Primary energy use

With the smallest windows, the use of the roller solar shading systems leads to an increase in the primary energy needs except for the configurations with the glazing DH, TH or TL coupled with the shade SH1 located externally. With the biggest windows and the shades located externally we obtain for all the configurations analyzed a reduction of the overall primary energy consumption except for the glazing DH coupled with the shade SH3. Essentially, considering that the use of the roller shading systems cause, in all the cases analyzed, an increase in the primary energy consumptions related with the lighting and heating systems, we can obtain a reduction of the overall primary energy needs only when the cut of the cooling needs is important enough to overcome the other two increases.

6. Conclusions

As we underlined before, one of the aims of this study is the representation of the fenestration system's influence on the overall performance of the confined environment. To reach this goal, we tried to build a methodology able to take into account at the same time the requirements of indoor thermal and visual comfort, the maximization of daylight availability and the reduction of the energy consumption due to heating, cooling and lighting systems. From a graphical point of view, we

Configuration	$sTC_{10,90\%}$ - IRRADIATED																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL
E_S1	56%	100%	67%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	89%	100%	89%	100%	67%	100%	67%	100%	67%	100%	67%	100%
E_S2	67%	89%	78%	100%	78%	89%	67%	100%	89%	89%	89%	100%	89%	89%	89%	100%	33%	78%	22%	78%	22%	67%	22%	78%	33%	67%	44%	67%

Fig. 1 – Spatial Thermal Comfort Irradiated

Configuration	$sTC_{10,90\%}$ - STANDARD																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL
E_S1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	89%	100%	89%	100%	67%	100%	67%	100%
E_S2	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	67%	100%	33%	100%	44%	100%	33%	89%	44%	67%	44%	67%

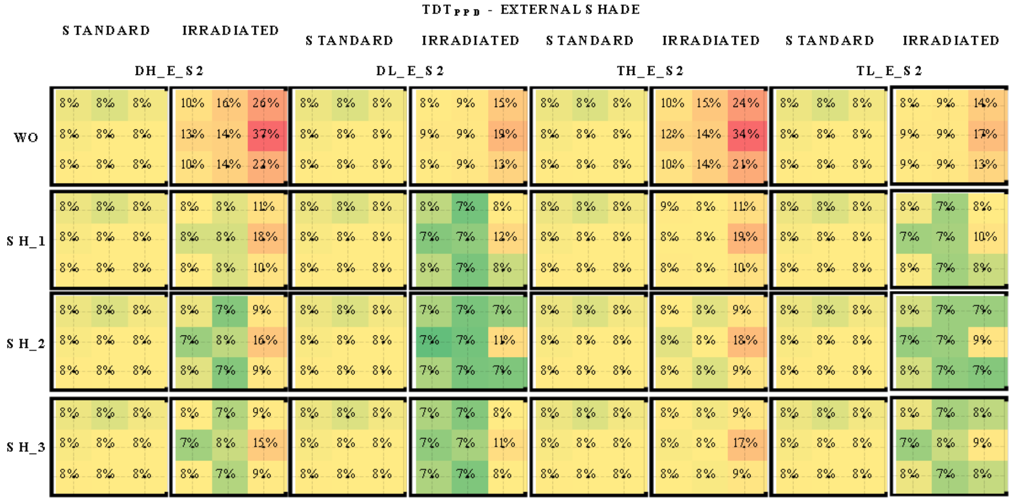
Fig. 2 – Spatial Thermal Comfort Standard

Configuration	$sDA_{500,50\%}$																											
	WO				$SH1_{ext}$				$SH2_{ext}$				$SH3_{ext}$				$SH1_{int}$				$SH2_{int}$				$SH3_{int}$			
	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL	DH	DL	TH	TL
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%

Fig. 3 – Spatial Daylight Autonomy

Configuration	$sVC_{0.35,100\%}$																											
	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%

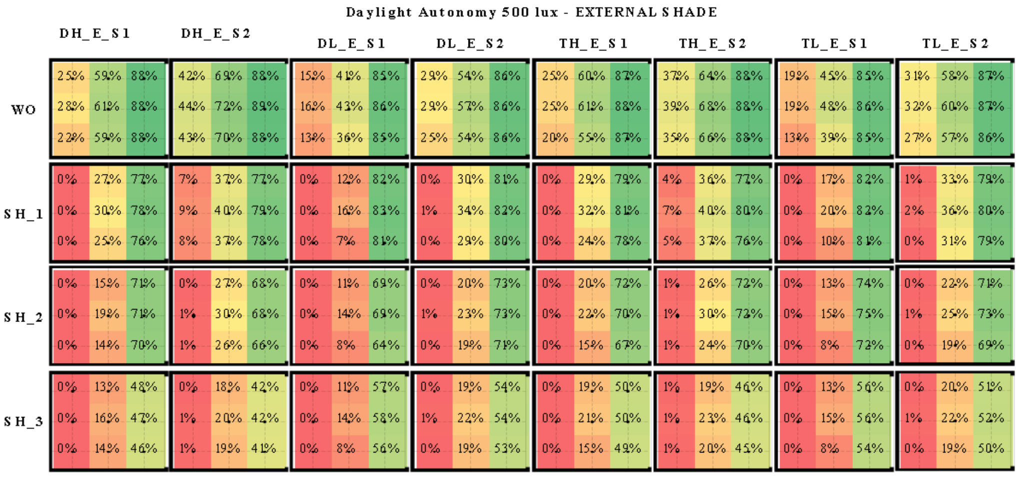
Fig. 4 – Spatial Visual Comfort



TDT_{PPD} - EXTERNAL SHADE

	DH_E_S2		DL_E_S2		TH_E_S2		TL_E_S2	
	STANDARD	IRRADIATED	STANDARD	IRRADIATED	STANDARD	IRRADIATED	STANDARD	IRRADIATED
WO	8% 8% 8%	10% 16% 26%	8% 8% 8%	8% 9% 15%	8% 8% 8%	10% 15% 24%	8% 8% 8%	8% 9% 14%
	8% 8% 8%	13% 14% 37%	8% 8% 8%	9% 9% 19%	8% 8% 8%	12% 14% 34%	8% 8% 8%	9% 9% 17%
	8% 8% 8%	10% 14% 22%	8% 8% 8%	8% 9% 13%	8% 8% 8%	10% 14% 21%	8% 8% 8%	9% 9% 13%
SH_1	8% 8% 8%	8% 8% 11%	8% 8% 8%	8% 7% 8%	8% 8% 8%	9% 8% 11%	8% 8% 8%	8% 7% 8%
	8% 8% 8%	8% 8% 18%	8% 8% 8%	7% 7% 12%	8% 8% 8%	8% 8% 19%	8% 8% 8%	7% 7% 10%
	8% 8% 8%	8% 8% 10%	8% 8% 8%	8% 7% 8%	8% 8% 8%	8% 8% 10%	8% 8% 8%	8% 7% 8%
SH_2	8% 8% 8%	8% 7% 9%	8% 8% 8%	7% 7% 7%	8% 8% 8%	8% 8% 9%	8% 8% 8%	8% 7% 7%
	8% 8% 8%	7% 8% 16%	8% 8% 8%	7% 7% 11%	8% 8% 8%	8% 8% 18%	8% 8% 8%	7% 7% 9%
	8% 8% 8%	8% 7% 9%	8% 8% 8%	7% 7% 7%	8% 8% 8%	8% 8% 9%	8% 8% 8%	8% 7% 7%
SH_3	8% 8% 8%	8% 7% 9%	8% 8% 8%	7% 7% 8%	8% 8% 8%	8% 8% 9%	8% 8% 8%	8% 7% 8%
	8% 8% 8%	7% 8% 15%	8% 8% 8%	7% 7% 11%	8% 8% 8%	8% 8% 17%	8% 8% 8%	7% 8% 9%
	8% 8% 8%	8% 7% 9%	8% 8% 8%	7% 7% 8%	8% 8% 8%	8% 8% 9%	8% 8% 8%	8% 7% 8%

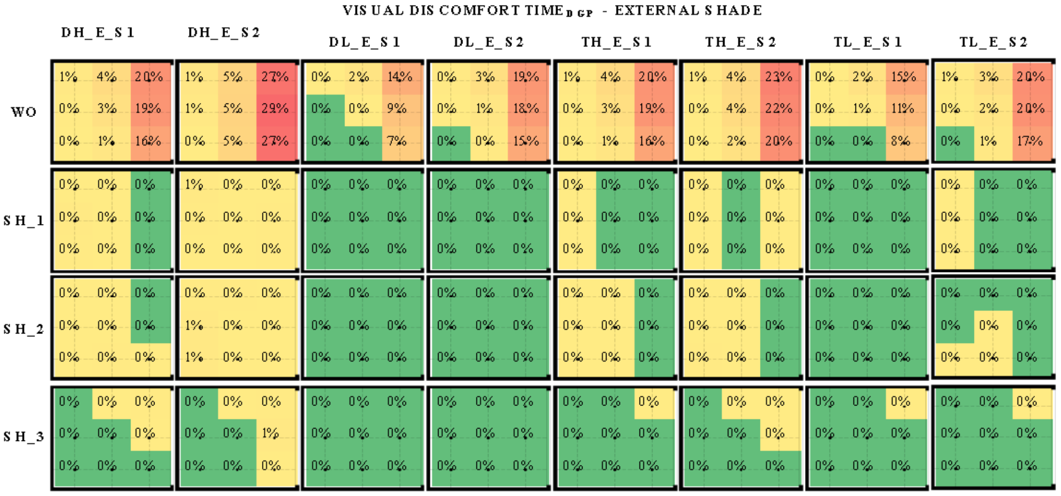
Fig.5 – Thermal Discomfort Time



Daylight Autonomy 500 lux - EXTERNAL SHADE

	DH_E_S1	DH_E_S2	DL_E_S1	DL_E_S2	TH_E_S1	TH_E_S2	TL_E_S1	TL_E_S2
WO	25% 59% 88%	42% 69% 88%	15% 41% 85%	29% 54% 86%	25% 60% 87%	37% 64% 88%	19% 45% 85%	31% 58% 87%
	28% 61% 88%	44% 72% 89%	16% 43% 86%	29% 57% 86%	25% 61% 88%	39% 68% 88%	19% 48% 86%	32% 60% 87%
	22% 59% 88%	43% 70% 88%	13% 36% 85%	25% 54% 86%	20% 55% 87%	35% 66% 88%	13% 39% 85%	27% 57% 86%
SH_1	0% 27% 77%	7% 37% 77%	0% 12% 82%	0% 30% 81%	0% 29% 79%	4% 36% 77%	0% 17% 82%	1% 33% 79%
	0% 30% 78%	9% 40% 79%	0% 16% 83%	1% 34% 82%	0% 32% 81%	7% 40% 80%	0% 20% 82%	2% 36% 80%
	0% 25% 76%	8% 37% 78%	0% 7% 81%	0% 29% 80%	0% 24% 78%	5% 37% 76%	0% 10% 81%	0% 31% 79%
SH_2	0% 15% 71%	0% 27% 68%	0% 11% 69%	0% 20% 73%	0% 20% 72%	1% 26% 72%	0% 13% 74%	0% 22% 71%
	0% 19% 71%	1% 30% 68%	0% 14% 69%	1% 23% 73%	0% 22% 70%	1% 30% 72%	0% 15% 75%	1% 25% 73%
	0% 14% 70%	1% 26% 66%	0% 8% 64%	0% 19% 71%	0% 15% 67%	1% 24% 70%	0% 8% 72%	0% 19% 69%
SH_3	0% 13% 48%	0% 18% 42%	0% 11% 57%	0% 19% 54%	0% 19% 50%	1% 19% 46%	0% 13% 56%	0% 20% 51%
	0% 16% 47%	1% 20% 42%	0% 14% 58%	1% 22% 54%	0% 21% 50%	1% 23% 46%	0% 15% 56%	1% 22% 52%
	0% 14% 46%	1% 19% 41%	0% 8% 56%	0% 19% 53%	0% 15% 49%	1% 20% 45%	0% 8% 54%	0% 19% 50%

Fig. 6 – Daylight Autonomy



VISUAL DISCOMFORT TIME$_{DGP}$ - EXTERNAL SHADE

	DH_E_S1			DH_E_S2			DL_E_S1			DL_E_S2		
WO	1%	4%	20%	1%	5%	27%	0%	2%	14%	0%	3%	19%
	0%	3%	19%	1%	5%	29%	0%	0%	9%	0%	1%	18%
	0%	1%	16%	0%	5%	27%	0%	0%	7%	0%	0%	15%
SH_1	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
SH_2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
SH_3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	TH_E_S1			TH_E_S2			TL_E_S1			TL_E_S2		
WO	1%	4%	20%	1%	4%	23%	0%	2%	15%	1%	3%	20%
	0%	3%	19%	0%	4%	22%	0%	1%	11%	0%	2%	20%
	0%	1%	16%	0%	2%	20%	0%	0%	8%	0%	1%	17%
SH_1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
SH_2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
SH_3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Fig. 7 – Visual Discomfort Time

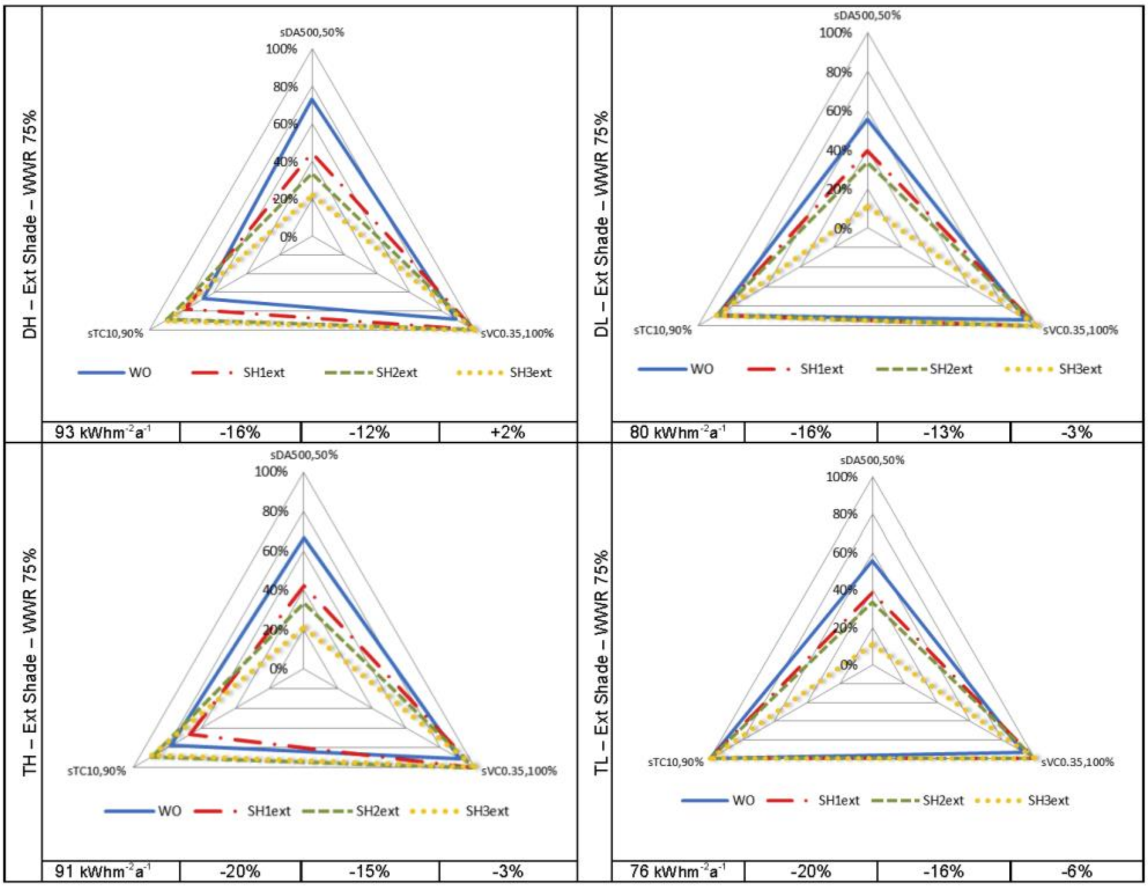


Fig. 8 – Integrated Performance

summarized through a single graph (Fig. 8) all the configurations analyzed by means of the variation of the synthetic metrics. We can notice that the settings used to ensure suitable internal visual and thermal comfort conditions for the occupants, with the specific orientation chosen, lead to a general increase of the total primary energy consumptions calculated. It is known that the building's energy consumption is related to the balance between gains and losses (climate, envelope and equipment) and this balance depends also on his operation. Whereas it is possible to predict the energy consumption related to envelope and equipment, the energy used to operate a building is strictly connected with the occupants' behavior, which is more difficult to predict. To maintain the building's energy use as close as possible to what we calculated, ensuring a satisfying internal environmental quality plays a very important role. The methodology proposed underlines:

i. the importance of analyzing together the overall performance of a building façade

ii. the contribution of simulation in the analysis of the integrated performance of façades and the necessity of using different simulation codes;

iii. the great importance of considering the effect of the direct and diffuse solar radiation on occupants well-being.

References

Apian-Bennewitz P., 2013. Review of Simulating Four Classes of Window Materials for Daylighting with Non-Standard Bsdf Using the Simulation Program Radiance. Retrieved 04/08, 2014, from http://arxivweb3.

Cappelletti F, Prada A., Romagnoni P., Gasparella A., 2014, Passive performance of glazed components in heating and cooling of an open-space office under controlled indoor thermal comfort, Building and Environment, vol. 72, p. 131-144.

Chan Y., Tzempelikos A., Protzman B., 2014, Solar optical properties of roller shades: modeling approaches, measured results and impact on daylighting and visual comfort, Proc. of High Performance Buildings Conference, West-Lafayette, USA.

La Gennusa M., Nucara A., Pietrafesa M., Rizzo G., 2007. A model for managing and evaluating solar radiation for indoor thermal comfort, Solar Energy vol. 81, p. 594–606.

Illuminating Engineering Society, 2012, Standard IES LM-83-12. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York, U.S.A.

Nabil A., Mardaljevic J., 2006. Useful daylight illuminances: a replacement for daylight factors. Energy and Buildings, vol. 38, p. 905–913.

Nielsen M.V., Svendsen S. et Jensen B. L. 2011. Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Solar Energy, vol. 85, p. 757-768

Ramos G., Ghisi E., 2010. Analysis of daylight calculated using the EnergyPlus programme. Renewable and Sustainable Energy Reviews, 14(7): p. 1948-1958.

Reinhart C.F., Jakubiec J.A., Ibarra D., 2013. Definition of a reference office for standardized evaluations of dynamic façade and lighting technologies, Proc. of Building Simulation, Chambery, France

Wienold J., Christoffersen J., 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy and Buildings, vol. 38, p. 743–75