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Assessment of long-term visual and thermal comfort and energy performance in open-space office with different shading devices

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ABSTRACT

Solar radiation can significant affect air-conditioning loads in buildings. Moreover, it has an impact on occupants' performance and well-being from a psychological and physiological point of view, influencing thermal and visual comfort conditions. However, large windows on building façades, facilitating daylight entry, may increase the risks of overheating or visual discomfort, requiring proper control of shading devices in order to prevent glare and direct solar radiation on the occupants. The hard task becomes defining a balance between those contrasting requisites, considering the specific application context and using different metrics in order to analyze both comfort and energy aspects.
In this paper, the effects of external and internal roller shades, both on thermal and visual comfort and on overall building energy demand, have been considered for the climatic condition of Rome (South Italy) in order to assess the long-term comfort conditions and energy performance of an open space office. Some office characteristics, such as windows extension, glazing type and shading characteristics has been changed in order to assess the performance under different conditions. The indoor thermal comfort levels are controlled by fixing adequate operative temperature set points while visual comfort is ensured through control of shading and lighting systems. Evaluation of building performance has been assessed through (i) total primary energy demand regarding energy aspects (ii) the Predicted Mean Vote and the Discomfort Time weighted by the Predicted Percent of Dissatisfied, including the effect of the diffuse and beam solar radiation, for analysis of thermal comfort and (iii) the Daylight Autonomy and the Daylight Glare Index for visual comfort.

1. INTRODUCTION

The relation between the effect of windows (glazing and shading device) on indoor conditions and energy consumption has been widely explored especially in office buildings where often aesthetic reasons make designers to choose transparent materials instead of opaque ones. The research on glazed buildings performance can be classified in four main fields depending on works' final purpose.

Some studies focus on the impact of the windows configuration on office buildings energy demand (Tsikaloudaki *et al.*, 2012, Kim *et al.*, 2012). In some cases, not only the geometrical, the thermal and optical characteristics on windows were investigated, but also different shading control strategies, based on behavioral models, has been evaluated in order to optimize the total energy demand (Correia da Silva *et al.*,2012).

In other studies, shading control has been investigated in relation to lighting energy use and visual comfort (Mahdavi and Dervishi, 2011). Nielsen *et al.* (2011) evaluated the total energy demand and the Daylight Factor considering different solar shading systems applied to different façade types. Shading performance assessment sometimes includes glare discomfort and the illuminance criteria (Oh *et al.*, 2012, Ochoa *et al.*, 2012). Shen and Tzempelikos (2013) considered 4 different shading control strategies evaluating their influence on the total energy consumption and visual discomfort, and validated the results through experimental measurements.

Other sets of studies focus on energy demand and thermal comfort. Hwang & Shu (2011) analyzed the effect of Taiwan regulation on thermal comfort and on the energy-saving potential for PMV-based comfort control in glass facade buildings. Frontini and Kuhn (2012) proposed a new method to evaluate the impact on Mean Radiant Temperature (MRT) of 4 different internal blinds, combined with 4 kinds of glazing, considering an on-off control strategy. Buratti et al. (2013) carried out an experimental campaign measuring several parameters in order to test and validate a simulation model with experimental data and then comparing different scenarios (glazing types and orientation) in terms of thermal comfort indices and cooling energy demand. A twin experimental and simulation study (Tzempelikos et al., 2010) investigated the impact of shading and glazing properties on thermal comfort, including solar radiation effects. Cappelletti et al. (2014) evaluated the energy glazing performance maintaining fixed comfort conditions and calculating the Predicted Mean Vote (PMV), taking into account the effect of the solar radiation as well.

Finally, a few recent papers have carried out complete studies on the effect of shadings on energy demand, thermal and visual comfort. Shen and Tzempelikos (2012) simulated a perimeter office calculating the total source energy consumption and verifying the thermal and visual comfort conditions under different climates, windows, glazing and shading properties. Sicurella et al. (2012) defined a statistical approach for the combined evaluation of indoor thermal and visual comfort evaluation, developing metrics able to take into account both the duration and the intensity of the potential discomfort related to thermal or visual conditions. Yao (2014) carried out field measurements and simulation analysis on a retrofitted residential building in China, considering heating and cooling needs and thermal and visual comfort conditions; they found that installation of external solar shadings allows to reach an energy saving potential equal to that obtained by reducing the wall insulation level to half of the energy standard, while installing low-e windows also improved thermal comfort and visual comfort conditions.

Among all these studies there aren't comprehensive studies which analyze both the overall energy demand (for heating, cooling and lighting) and the comfort conditions (both thermal and visual); moreover in most of the cases the metrics used to assess the thermal comfort do not consider the effect of solar radiation on the long term thermal comfort conditions and space distribution.

In this paper, the effects of external and internal roller shades, both on thermal and visual comfort and on overall building energy demand, have been considered for the climatic conditions of Rome. An open-space office with windows distributed on a single façade or on opposite façades, and directed towards 2 orientations (South or South/North and East or East/West) has been simulated. The window area and the glazing system have been changed in order to evaluate the shading performance in several office configurations. The thermal comfort indoor conditions have been controlled by fixing adequate operative temperature set points. Shades with three different levels of solar and light transmission coefficients have been chosen for the comparison. To fulfill occupant visual comfort, the shades are controlled based on two set points: a limit glare index of 22 DGI and the maximum total solar radiation incident on the windows fixed at 150 W m^{-2}. An illuminance level of 500 lux during the hours of occupation is guaranteed by dimmable artificial lighting.

Concerning the energy performance, the office primary energy demand for heating, cooling and lighting have been calculated. The assessment of the long-term comfort conditions has been conducted on a seasonal basis, taking into account both the thermal and visual comfort conditions. Regarding thermal comfort, the PMV and the Discomfort Time weighted by the Predicted Percent of Dissatisfied (WDT_{PPD}) have been calculated in 9 points in the office, including also the effect of the diffuse and beam solar radiation directly reaching the occupants (Cappelletti et al., 2014). The visual comfort has been assessed using spatial Daylight Autonomy (sDA) and the Discomfort Glare Index (DGI).

2. SIMULATION PARAMETERS

2.1 Geometrical Model and Characteristics of Components

The model is an open space office of 100 m^2 of floor area and 3 m of interior height. Vertical walls and roof are all external while the floor is modelled as adiabatic. The composition of all the opaque elements, both vertical walls and roof slab, is identical, with a 20 cm thick internal layer of clay block and a 5 cm thick external insulation layer. The structure has a thermal transmittance of 0.45 W m^{-2} K^{-1}. The solar absorptance is 0.6 for the floor (internal side) and 0.3 for the vertical walls and the roof (both sides). The wall emissivity is 0.9, both for the internal and the external side. The light reflection coefficients have been set to 0.4 for the floor (internal side) and 0.7 for the vertical surfaces (both side) and for the ceiling. A parametrical analysis has been performed by varying the building envelope parameters summarized in Table 1, and in particular considering three different types of roller shades in two position (inside and outside of the windows).

2.2 Internal Gains

The office is occupied from 8:00 am to 6:00 P.M., Monday to Friday. The occupancy index has been fixed as 0.12 people m^{-2}. The occupants' metabolic heat flux is equal to 70 W m^{-2} or 1.2 met. The heat flow is divided into the sensible portion of 75 W (58% as radiant exchange) and latent heat of 55 W. The clothing unit thermal resistance is 1 clo during the winter season (from 1st October to 31st March), and 0.5 clo during the summer (from 1st April to 30th September). People view direction is parallel to the window. The internal loads related to electrical equipment are quantified considering 12 personal computers, 12 monitors, a laser printer and a copier, with constant average power during the occupation period. The considered Light Power Density (LPD) is 12 W m^{-2}, with fluorescent lamps installed on the ceiling.

Table 1: Variables used in the analysis

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

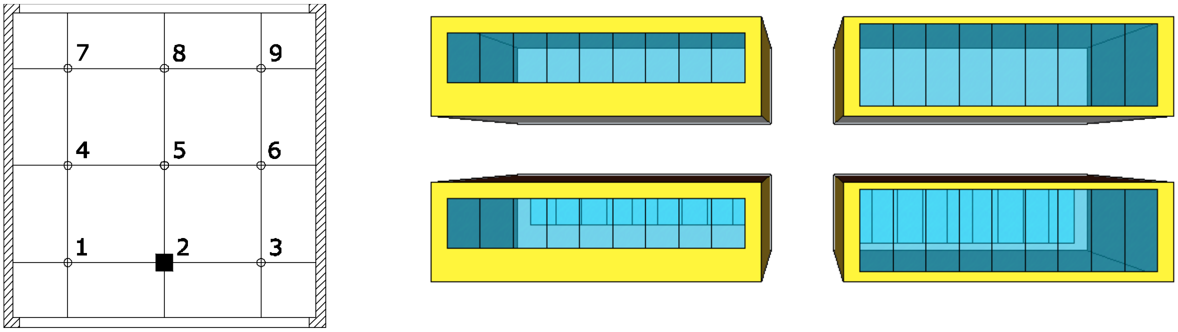

Figure 1: Plan of the office model and occupants' positions for the PMV calculations; and 3D-models of the different cases simulated.

2.3 Energy Performance, Visual and Thermal Comfort Setting

During the occupation period, artificial lights are dimmed depending on the level of natural illumination, in order to maintain 500 lux on the work plane area. The shading devices close when external total solar radiation on the window surface exceeds 150 W m^{-2}. This setpoint value has been chosen considering that people don't usually shut the shades when solar radiation is below 50-60 W m^{-2} while normally they need to close them above 250–300 W m^{-2} (Reinhart, 2004). A second control criterion is based on a Daylight Glare Index (DGI) limit value of 22 for the position 5 (Fig. 1), which corresponds to a value of Unified Glare Rating (UGR) of 19, in order to ensure comfort inside the confined spaces for office use. The heating and cooling system is controlled considering two bands for the operative temperature, 20 °C to 24 °C for winter and 23 °C to 26 °C for summer, during weekdays, to comply with the comfort Category II (normal level of expectation about the conditions of comfort for users). 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 during unoccupied periods, and the cooling set-point is fixed in order to guarantee that the cooling system is switched off outside the occupancy period. To assess the comfort conditions inside the office, a grid consisting of 9 points at 0.8 m from the floor level was considered.

3. PERFORMANCE METRICS

The thermal comfort conditions have been evaluated during the occupancy period. Besides the standard PMV, a corrected PMV (PMV_{irr}) has been calculated for all the positions considering the effect of solar radiation that directly reaches the occupant, based on the work of La Gennusa et al. (2007). For this aim, a new mean radiant temperature (MRT_{irr}) was determined by adding to the standard MRT the contributions of diffuse and the beam solar radiation entering through the windows and reaching the occupant:

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

The long-term comfort performance is also evaluated, for each season, by the PPD-weighted discomfort time (WDT_{PPD}) that is the number of hours during which the PMV (either standard or with irradiation PMV) overcomes the comfort category range, in this case ±0.5 (category B), weighted by a factor calculated as follows:

$$wf = \frac{PPD}{PPD_{\lim}} \qquad (2)$$

where PPD_{lim} is the acceptable limit for the considered comfort category, i.e. 10 % for the category B, and PPD is the hourly Predicted Percentage of Dissatisfied (standard or corrected for irradiation effect). The weighting factor becomes 1 when 10 % of the occupants are dissatisfied. During each season the WDT_{PPD} should be calculated separately for cool (PMV < -0.5) and warm (PMV > 0.5) sensation respectively.

Considering the definition of the WDT_{PPD}, the ratio between this quantity and the corresponding (not weighted) Discomfort Time, DT, represents the average weighting factor that is the average percentage of dissatisfied people during all the DT. In particular, with a PPD_{lim} of 10 %, a WDT equal to the DT means that, during the discomfort time, 10 % of people (on average) are dissatisfied. With a WDT twice as much of DT, the average percentage of dissatisfied would be 20 % and so on.

Also, the visual comfort conditions were evaluated only during the occupation period. For each configuration without shades, the main climate-based Daylighting Metrics (Daylight Autonomy, DA and spatial Daylight Autonomy, sDA) were calculated to summarize annual daylighting performance throughout the space (IES, 2012). sDA provides a measure of daylight illuminance sufficiency for a given area, reporting the percentage of floor area that exceeds a specified illuminance level (e.g. 300 lux) for a specified amount of annual hours (e.g. 50% of the hours from 8am-6pm). In our analysis we have chosen an illuminance threshold of 500 lux. For the SH1 and SH3 configurations only the DA has been calculated, taking into account the shading operation schedule obtained from the energy simulation. A suitable materials file has been created in order to describe all the envelope elements like Radiance material primitive. In particular, we used the material primitive *Plastic* for the opaque elements, *Glass* for the transparent ones and *Trans* for the roller solar shades. Besides the daylight availability, discomfort glare has been analyzed by calculating the number of hours during which the Daylight Glare Index exceeds the limit value of 22.

Finally heating, cooling and lighting energy performance have been evaluated in terms of primary energy use for small and large windows in order to allow the comparison through a single global indicator. Conventional values of

0.8 as seasonal thermal energy production efficiency, 3 as seasonal Energy Efficiency Ratio for cooling and 2.174 primary energy content per unit of electrical energy were assumed as it is for the Italian electrical system. As described in Cappelletti *et al.* (2014), given the control modality of the heating and cooling system by means of the operative temperature set-point, the energy demand to be interpreted as a double indicator of the passive energy and comfort condition performance of the envelope, being the energy performance of different cases compared under equivalent comfort conditions.

4. RESULTS

4.1 Indoor thermal comfort

The effect of shading devices coupled with different types of glazing on indoor thermal comfort has been evaluated. Given the temperature set-point set in the simulation, the thermal comfort band of ±0.5 PMV_{st} should be assured; nevertheless, solar radiation reaching the occupant and windows surface temperatures can cause discomfort (warm sensation); also, window surface temperatures can lead to slightly cool sensation, especially for positions near the windows, as highlighted by Cappelletti et al. (2014). Table 2 show the weighted number of hours of discomfort at the 9 positions in the office: each rectangle in the table represents the office plan configuration with the north on the left part of the page. Each rectangle is divided into 9 colored cells with the number of discomfort hours inside; colors are scaled according to the entity of the discomfort time. For space reasons just the configurations with double glazing and with small windows is presented in the paper. We can assume similar trends for triple glazing and large windows.

During winter the warm sensation overcomes the cool sensation.

The presence of shades mitigates the number of discomfort hours. This is particularly important for the critical configuration of windows oriented towards south and for a glazing system with high SHGC: in this case internal shades halve the highest discomfort time near the windows, while external shades can reduce the time of about 80%. Taking the case without shading as reference we can comment on some trends. The maximum advantage in reducing discomfort is given by external shades rather than internal shades. With internal shades the positions exposed to solar radiation have a discomfort time period which is twice the one with external shades. In general, the discomfort time is reduced with internal shades, even though with DL glazing it slightly increases at points far from the windows. Comparing the three types of shades we can see that, when positioned externally, their efficiency depends on the solar transmission coefficient: thus shade SH2 is better than SH1 and SH3 is better that SH2. For internal shades, there is not a specific trend and the three shades have similar efficacy.

During summer the weighted discomfort time is lower than in winter.

The presence of shades increases the discomfort time at points not reached by solar irradiation, while they are very useful to mitigate the warm discomfort at west and south positions.

Both internal and external shadings assure good indoor thermal comfort. In general the WDT_{PPDirr} is a bit higher for external shades: this is a consequence of the type of control used for the heating and cooling set-point. Giving a set-point for the operative temperature, the air temperature controlled by the system depends on the MRT value at each time step, thus leading to situations in which even though the indoor MRT is lower with external shades, the air temperature is higher and the sensation is warmer than with internal shadings. The efficacy of the three shades is similar when located on the external side of the windows, while on the internal side SH2 and SH3 are slightly preferable than SH1.

A detailed analysis of the influence of shading devices on position 2 (see Figure 1) has been carried out because point 2 is the one mostly influenced by the solar radiation through the window (Figure 2). In winter at point 2 the discomfort sensation is due to the warm feeling. The presence of external shades neutralizes the dependence of the comfort sensation from the windows orientation; while with internal shades South exposition gives the higher discomfort. As previously said, external shading ensures better conditions compared to internal devices. In Figure 2, the black and white columns represent respectively the WDT_{PPDirr} and the $WDT_{PPDst,}$ being the first calculated considering the solar radiation hitting the occupants and the second not considering the solar correction: it can be noted that with external shades the two indices are almost the same. On the contrary, with internal shading, the contribution of solar radiation on thermal discomfort is important just when shades are coupled with high SHGC glazings and in particular for South and South-North orientation.

Looking at the summer season the discomfort time is very low, both with internal and with external devices. Considering the $WDT_{PPDst,}$ the sensation would be of cool feeling and more than the 10 % of people would seem to be dissatisfied, while taking into account the solar radiation, as it is in the real situation, it can be seen that the use of shading always assures no more than the 10% of people dissatisfied.

Table 2: Spatial distribution of the Weighted Discomfort Hours during the winter (dashed line - - -) and summer season (solid line —)

		DH_E_ S1			DH_EW_ S1			DH_S_ S1			DH_NS_ S1			DH_E_ S1			DH_EW_ S1			DH_S_ S1			DH_NS_ S1		
	W/O	6	6	74	400	48	72	15	12	16	3	8	3	252	284	559	654	408	631	146	225	143	275	459	285
		6	7	111	468	47	103	9	11	9	3	3	3	253	252	599	735	362	698	294	253	333	359	332	403
		11	6	75	400	43	74	46	166	39	41	90	32	205	267	373	490	331	409	1101	1503	1244	1143	1587	1297
External Shadings	SH1	28	26	35	30	15	27	48	27	50	11	13	11	183	184	198	251	236	242	171	195	166	242	278	244
		26	35	31	58	19	26	27	37	27	14	16	14	183	173	220	279	220	271	191	178	194	244	226	246
		46	26	35	30	15	27	35	15	30	26	10	22	164	183	189	237	229	229	213	257	227	255	313	280
	SH2	27	26	29	18	17	22	47	29	49	12	16	12	180	182	191	222	217	221	160	176	157	219	248	221
		26	37	25	9	22	21	29	46	29	17	23	16	181	173	210	245	201	241	175	164	177	217	205	219
		44	26	29	18	17	22	32	13	29	26	12	24	164	181	187	213	213	210	184	215	198	223	255	233
	SH3	28	29	29	20	21	24	45	26	47	16	19	14	181	183	189	210	204	205	160	181	159	205	231	205
		28	38	32	14	28	15	28	42	28	20	24	20	181	174	208	225	193	226	181	167	181	201	189	201
		45	31	29	20	21	25	34	18	34	28	11	28	165	181	186	206	201	200	181	204	192	194	223	206
Internal Shadings	SH1	23	16	18	25	3	10	25	18	25	5	2	5	233	244	283	370	298	340	166	228	159	299	463	307
		23	25	21	67	6	16	16	22	16	7	11	7	235	221	309	432	271	410	252	215	262	303	269	313
		28	16	19	25	3	10	13	10	12	9	6	6	197	241	270	352	280	311	464	581	501	513	636	548
	SH2	8	8	8	3	3	4	22	16	23	4	2	4	234	245	307	367	278	327	136	193	124	236	402	243
		8	11	16	18	3	9	13	19	13	6	9	6	234	220	344	445	255	410	229	191	239	265	246	273
		16	8	8	3	3	4	7	9	8	5	4	4	195	243	292	355	255	306	531	644	563	558	676	587
	SH3	8	5	6	3	3	3	16	10	17	5	0	5	244	252	341	375	256	319	118	163	116	193	338	197
		8	9	10	5	4	4	10	13	10	5	6	5	244	231	392	458	227	404	189	162	200	230	208	238
		14	5	6	3	3	3	5	3	6	4	6	5	206	250	333	360	243	301	568	702	596	580	717	607
		DL_E_ S1			DL_EW_ S1			DL_S_ S1			DL_NS_ S1			DL_E_ S1			DL_EW_ S1			DL_S_ S1			DL_NS_ S1		
	W/O	51	36	43	164	27	32	42	23	44	16	11	15	176	205	233	326	263	271	167	229	163	210	318	212
		38	35	34	188	31	31	22	26	22	13	18	13	204	205	256	363	243	323	259	224	266	267	239	279
		51	36	43	163	27	32	31	29	23	24	23	18	176	204	214	301	249	239	404	504	444	423	540	466
External Shadings	SH1	35	37	36	30	27	32	58	33	59	29	10	29	167	166	166	180	180	176	155	173	155	182	202	184
		34	53	16	14	39	16	34	54	34	29	38	29	167	157	182	200	170	196	172	158	173	188	174	188
		65	37	36	30	27	33	40	14	40	35	14	35	154	166	165	177	177	171	172	196	178	187	209	193
	SH2	36	37	38	36	30	36	53	29	57	31	11	31	168	167	167	172	173	170	154	170	152	171	190	172
		36	55	13	13	46	13	31	50	30	31	44	31	168	159	181	185	163	184	169	157	169	174	163	175
		63	37	40	36	30	37	36	17	36	39	19	39	157	166	166	169	170	167	167	186	172	170	196	176
	SH3	32	35	43	36	34	41	49	26	51	31	11	31	170	170	167	165	166	161	162	179	160	164	179	165
		32	51	16	17	43	14	31	46	31	34	43	34	170	159	184	178	156	179	177	166	177	167	157	167
		59	38	43	36	34	43	39	19	38	45	22	45	157	169	167	162	164	159	175	192	177	161	178	166
Internal Shadings	SH1	43	41	31	24	23	20	38	26	40	22	9	22	203	202	209	258	243	231	199	265	194	260	314	263
		43	50	15	16	27	14	25	31	25	21	24	21	203	190	227	286	221	272	270	240	272	280	246	283
		58	41	31	24	23	20	20	13	20	22	9	22	180	202	205	253	232	217	297	342	307	314	365	327
	SH2	44	41	29	25	22	20	32	24	33	18	9	18	214	214	218	265	246	235	172	254	167	232	323	241
		44	47	11	16	25	10	24	29	24	15	25	15	214	198	239	298	222	282	268	224	270	276	242	277
		54	42	29	25	22	20	18	9	18	14	5	14	179	213	215	259	236	223	319	373	331	326	374	335
	SH3	36	35	27	20	17	16	30	21	30	18	9	18	215	221	231	266	241	228	160	221	151	212	322	217
		36	42	10	15	22	7	21	25	21	16	21	16	215	201	254	306	214	281	245	197	247	270	225	272
		46	35	27	20	18	16	16	6	17	13	5	13	184	221	229	263	234	224	349	402	358	333	391	345

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4.2 Indoor visual comfort

Table 4 shows the spatial Daylight Autonomy, sDA, for the cases without shadings and with shades SH1 and SH3 positioned at the external side of the windows. The DL and TL glazing systems guarantee the same sDA being characterized by the same visible transmittance. We used the threshold limits suggested by IESNA: a $sDA_{500,50\%}\geq 55\%$ allows to consider the space "neutral" or "nominally acceptable"; a $sDA_{500,50\%}\geq 75\%$ allows to consider the space "preferred".

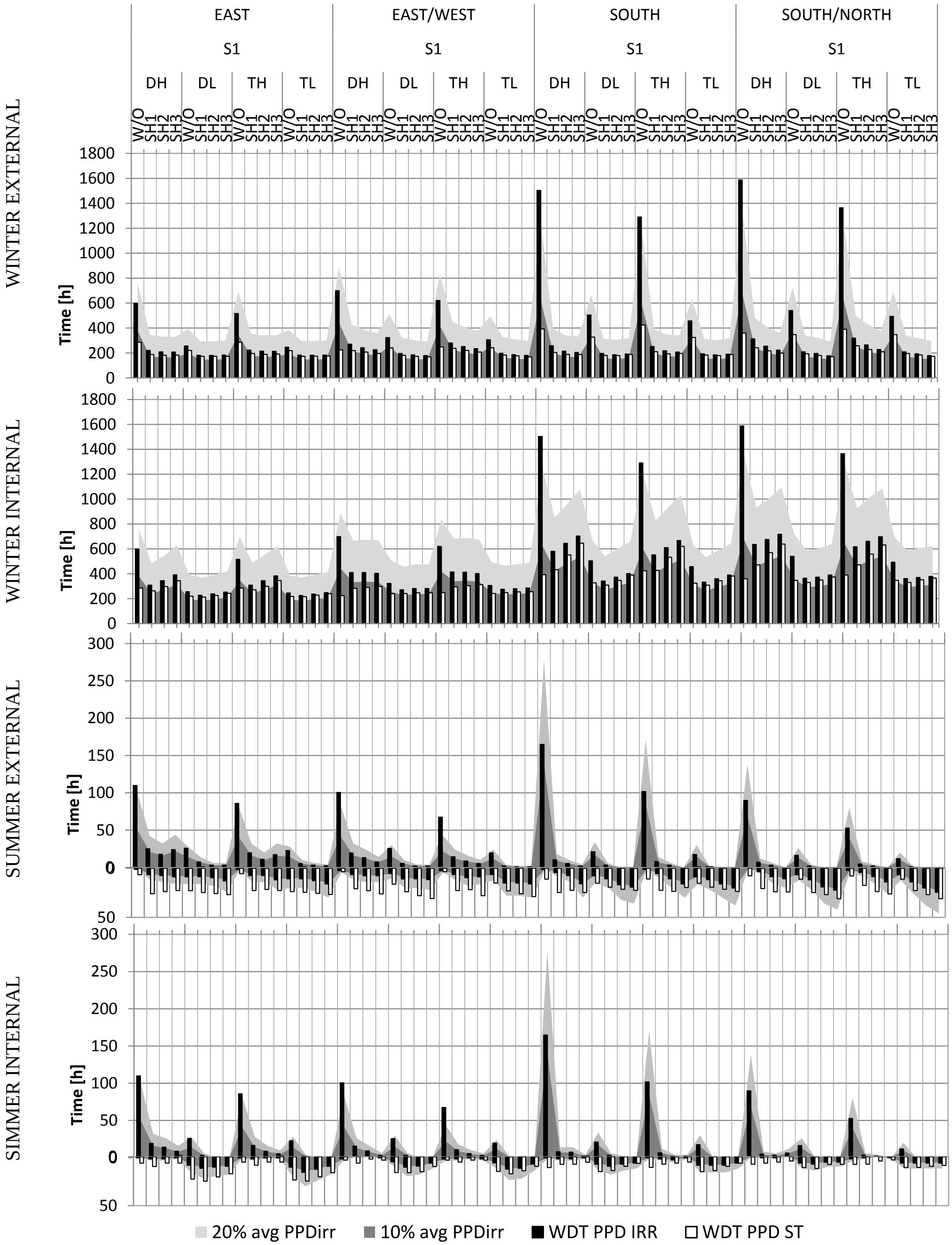

Figure 2: WDT in P2 winter and summer season with small windows. Above zero: warm sensation; below zero: cold sensation

If we consider the configuration without shades, we can notice that only the solution with the double glazed façade is able to ensure the threshold requested regardless from the glazing system chosen. Considering the space dimensions, it is clear that a single glazed façade is able to reach the threshold value only with the bigger windows oriented towards South, and with a high SHGC glazing system. The roller shades SH1 and SH3, because of the control schedule chosen, that limits the glare condition, always prevent an acceptable daylight autonomy.
Relative to glare evaluation, for configurations without shading devices for the S or S+N orientations, the point P2 results indicate more than 600 discomfort hours per year with small windows, independent of the glazing type. This means that the occupants in position 2 will fall under conditions of visual stress for about 30% of their working time. In this geographical location and according to the simulation code used for simulations, the use of the three roller shades chosen for this study (internal and external) eliminate glare hours. Note however, that, if Daylight Glare Probability is used instead of DGI, glare is bound to occur even with closed shades, since vertical illuminance will be significant close to the windows and direct-direct transmission through fabrics will be taken into account. Further studies are needed to investigate differences between glare indices.

Table 4: Spatial Daylight Autonomy for windows without shadings and with shades SH1 and SH3

Configuration	**$sDA_{500,50\%}$**								
	WO			**SH1**			**SH3**		
	DH	**DL/TL**	**TH**	**DH**	**DL/TL**	**TH**	**DH**	**DL/TL**	**TH**
S_S1	53%	47%	49%	28%	21%	27%	5%	0%	10%
S_S2	57%	51%	56%	30%	22%	27%	10%	11%	11%
SN_S1	100%	100%	100%	37%	22%	23%	11%	9%	10%
SN_S2	100%	100%	100%	40%	25%	33%	11%	10%	11%
E_S1	40%	33%	37%	11%	10%	11%	0%	0%	0%
E_S2	43%	33%	40%	11%	11%	11%	0%	0%	0%
EW_S1	100%	100%	100%	30%	22%	22%	5%	0%	0%
EW_S2	100%	100%	100%	31%	22%	26%	4%	0%	25%

4.3 Heating, cooling and lighting energy use

In figure 4 the primary energy demand for heating, cooling and lighting is plotted for small windows cases. The comparison between the primary energy in the office with and without shades allows shading energy performance evaluation. As already highlighted (Atzeri *et al.* 2014), the introduction of shades can affect the energy performance of the office in different ways, depending on their type and position, window orientation and size. The use of shading systems (internal and external) will increase lighting needs compared to no shading. However, while for the external position cooling needs are reduced and heating are slightly increased, internal shades may result in increase of cooling needs that cannot be compensated by a corresponding reduction of heating requirements, depending on reflectivity and solar transmission. Therefore, external systems perform better than internal ones from an energy point of view. Otherwise it is important to focus that these results strictly depend on shade properties and controls as well as climatic conditions. Reflective internal shades can reduce cooling requirements significantly.Moreover, internal shades can be a good solution for heating-dominated climates where the energy demand for heating prevails over that for cooling .

5. CONCLUSIONS

In this paper the integrated performance of three shading devices is presented. Performance has been assessed considering thermal and visual comfort conditions besides overall energy demand of an open space office. For the evaluation, long-term indicators have been used and the comfort distribution over the space is presented. The use of shades is necessary in order to prevent visual and thermal discomfort while, on the other side, the use of shades may result in increased energy demand, especially for south-facing facades. Moreover, shading devices can hamper the use of daylighting as denoted by the analysis, even though they prevent from glare problems. Therefore efficient shading controls are necessary.
Two aspects should be further investigated: a comprehensive indicator for the assessment of shading performance and the application of a multi-objective analysis to find the optimal compromise between indoor comfort and energy demand. A further development of this work will focus on these objectives.

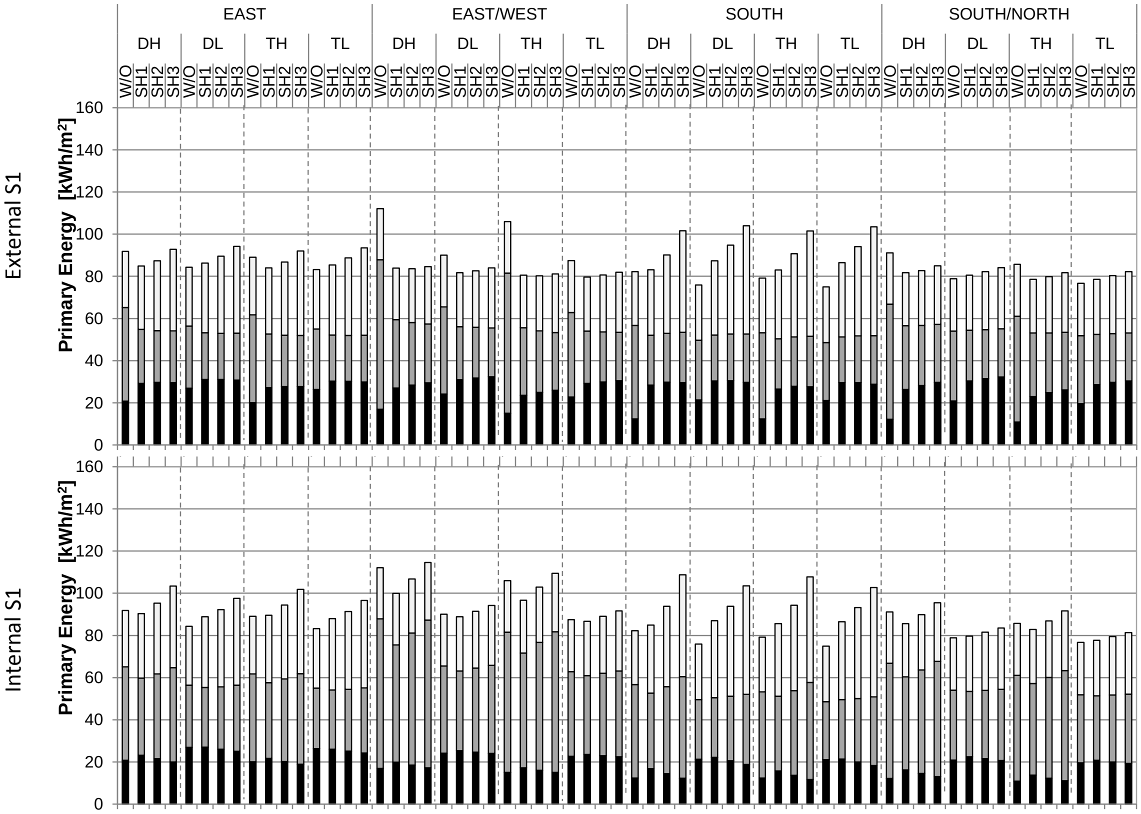

Figure 4: Primary Energy for heating, cooling and lighting with external and internal shading devices in the case of small windows.

NOMENCLATURE

CDD_{18}	Cooling Degree Days with reference temperature 18 °C	(Kd)
DA	Daylight Autonomy	(%)
DGI	Daylight Glare Index	(-)
$F_{S\rightarrow i,j}$	Angle factor between the window and the person	(-)
f_p	Projected area factor of the subject in the solar beam direction	(-)
HDD_{18}	Heating Degree Days with reference temperature 18 °C	(Kd)
I_d^{in}	Intensity of inner diffuse solar radiation	(W m^{-2})
I_{bn}^{in}	Intensity of indoor beam solar radiation on a surface orthogonal to solar ray direction	(W m^{-2})
MRT	Mean radiant temperature	(K)
PPD	Predictive Percentage of Dissatisfied	(%)
PMV	Standard Predicted Mean Vote	(-)
OT	Operative Temperature	(K)
sDA	Spatial Daylight Autonomy	(%)
$SHGC$	Solar Heat Gain Coefficient	(-)
T_i	Temperature of surface i	(K)
U_{gl}	Glazing thermal transmittance	(W m^{-2} K^{-1})
WDT_{PPD}	PPD-Weighted Discomfort Time	(h)
Subscripts		
irr	When the index take into account the effect of solar irradiation hitting the occupant	
st	For a standard calculation of the index	
Greek Symbols		
$\alpha_{\mathrm{irr,\ d/b}}$	Absorption coefficient of the subject referring to the diffuse or beam solar radiation	(-)

ε	Emissivity of the subject	(-)
σ	Stephan- Boltzmann constant	(W $m^{-2}K^{-4}$)
$\tau_{d\,/\,b}$	solar transmittance for diffuse or beam solar radiation	(-)
$\tau_{s/v}$	shades solar and visible transmittance	(-)
$\rho_{s/v}$	shades solar and visible reflectance	(-)

REFERENCES

CEN, 2005, Standard EN 7730:2005 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

CEN, 2002, Standard EN 12464-1:2002: Lighting of work places Part 1: Indoor work places.

CEN, 2007, Standard EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

C. Buratti, E. Moretti, E. Belloni, F. Cotana, 2013, Unsteady simulation of energy performance and thermal comfort in non-residential buildings, *Building and Environment* , vol. 59, p. 482-491.

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.

Correia da Silva P., Leal V., Andersen M., 2012, Influence of shading control patterns on the energy assessment of office spaces. *Energy and Buildings*, vol. 50, p. 35-48.

Frontini F., Kuhn T. E., 2012, The influence of various internal blinds on thermal comfort: A new method for calculating the mean radiant temperature in office spaces., *Energy and Buildings*, vol. 54, p. 527-533.

Kim G., Lim H. S., Lim T. S., Shaefer L. et Kim T. J. 2012. Comparative advantage of an exterior shading device in thermal performance for residential buildings, *Energy and buildings*, vol. 46, p. 105-111.

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.

Hwang Ruey-Lung & Shu Shiu-Ya, (2011), Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control, *Building and Environment*, vol. 46, p.824-834.

Illuminating Engeneering Society, 2012, Standard IES LM-83-12. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York, United States

Mahdavi A. et Dervishi S. 2011. Exploring the energy performance of simulation-powered lighting and shading systems controls in buildings, *Proc. of Building Simulation 2011,* Sydney, Australia

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

Ochoa C. E., Aries M. B. C., van Loenen E. J. et Hensen J. L. M. 2012. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, *Applied Energy*, vol. 95, p. 238-245

Oh M. H., Lee K. H., Yoon J. H., 2012, Automated control strategies of inside slat-type blind considering visual comfort and building energy performance., *Energy and Buildings*, vol. 55, p. 728-737.

Reinhart, C.F., 2004. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. *Solar Energy* 77, p. 15–28.

Shen H., Tzempelikos A. 2012. Daylighting and energy analysis of private offices with automated interior roller shades, *Solar Energy*, vol. 86, p. .681-704

Tzempelikos A., Shen H., 2013. Comparative control strategies for roller shades with respect to daylighting and energy performance. *Building and Environment*, vol. 67, p. 179-192.

Sicurella F., Evola G., Wurtz E. 2012 A statistical approach for the evaluation of thermal and visual comfort in free-running buildings. *Energy and Buildings*,vol. 47, p.402-410.

Tsikaloudaki K., Theodosiou T., Laskos K., Bikas D., 2012, Assessing cooling energy performance of windows for residential buildings in the Mediterranean zone. *Energy and Building*, vol. 64, p. 335-343.

Tzempelikos A., Bessoudo M., Athienitis A. K., Zmeureanu R., 2010. Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties, Building and Environment. 45, p. 2517–2525.

Yao J., 2014, An investigation into the impact of movable solar shades on energy, indoor thermal and visual comfort improvements, *Building and Environment*, vol. 71, p. 24-32