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Influence of shading control patterns on the energy assessment of office spaces

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ABSTRACT

This work reviews existing models of control patterns for occupant–shading interactions in office buildings, and studies their influence in terms of energy demand when comparing transparent façade alternatives. It starts by establishing a review of visual comfort criteria in office buildings and of the conditions that prompt occupants to interact with shading devices and electric lighting. Given the large variety of parameters identified as primary variables in the existing literature – hence the variety of conditions considered comfortable depending on the chosen reference – a sensitivity study was carried out based on dynamic simulations. The aim of the study was to characterize the impact of choosing a given shading control model (pattern or strategy) on the calculated overall energy demand for heating, cooling and lighting, as well as the impact on choosing the best-performing transparent façade option for a single-occupant office. The results show that both the calculated energy performance and the ranking of transparent façade alternatives (glazing and shading) often vary very significantly with control patterns considered for the occupant-shading interaction. They further show that, amongst the eleven control strategies that were considered, the behavioral model based on a glare acceptability threshold (expressed as DGI > 20) is the one that, when considered individually, would most reliably express an average ranking from all considered strategies. The implications of these findings are discussed in view of their applicability to energy performance-based façade design choices evaluation as well as to façade design choices.

1. Introduction

Glazed surfaces have an impact on the energy demand for lighting, heating and cooling of buildings. Combined, they typically account for more than 50% of the overall energy demand of office buildings in OECD countries and often even as much as over 70% [1]. The adoption of design methods to select glazing and shading devices should lead to the choice of solutions that ensure a good level of energy efficiency, while guaranteeing esthetical quality and visual comfort to building occupants.

It is common knowledge that building occupants tend to adjust the lighting and shading devices dynamically, as a function of the indoor and outdoor environmental conditions and of the way these conditions might impact their visual comfort perception, in addition to other behavioral motivations independent of their environment. The drivers for this behavior have typically been reported in the forms of workplane illuminance [2–5], luminance [6,7], glare indexes [8,9], solar radiation [6,8,10–13] and/or occupation period [12,14].

Although occupant behavior is therefore the result of multiple factors and criteria, the most commonly used methods to evaluate heating and cooling annual demand typically assume that shading devices remain in a fixed position during heating and cooling season. This assumption has in fact been adopted by the building energy regulations of many countries, such as the RSECE in Portugal [15,16]: it assumes that movable shadings are never active during the heating season, and that 70% of the glazing area is shaded during the cooling season. On the other hand, the EN ISO 13790 [17] recommends a more dynamic method, based on the assumption that the shading devices are used whenever the intensity of the solar irradiation on the window exceeds 300 W/m^2. Regarding electric lighting, the typical assumption in terms of energy consumption evaluation is that it relies on user-defined and fixed daily/weekly/seasonal schedules [18]. As such, it can, again, be considered a non-dynamic approach.

Parameters for deterministic control patterns (static thresholds), including workplane illuminance, glare indexes and solar radiation, are already integrated in simulation frameworks like

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List of symbols and abbreviations

VDT video display terminal
$E_{Workplane\ Daylight}$ workplane average illuminance due solely to daylight (lux)
E_{Max} maximum illuminance of the task area (lux)
E_{Min} minimum illuminance of the task area (lux)
E_{Task} average illuminance of the task area (lux)
$E_{Surround}$ illuminance of the immediate surrounding task area (band with a width of at least 0.5 m) (lux)
L_{Window} average window luminance (cd/m^2)
$L_{Visual\ field}$ luminance distribution of the field of view (cd/m^2)
$L_{Surround}$ luminance of the immediate surrounding task area (band with a width of at least 0.5 m) (cd/m^2)
L_{Paper} paper luminance (cd/m^2)
$L_{Surround-}$ task surrounding surfaces luminance (–)
L_{VDT} VDT luminance (cd/m^2)
U-value coefficient of heat transmission (W/(m^2 °C)
g-Value total solar transmittance through windows (–)
T_{Sol} solar transmittance through windows (–)
T_{Vis} light transmittance through windows (–)

EnergyPlus [19], ESP-r [20] or TRNSYS [21]. The main assumption there is that shading devices or electric lighting are activated whenever the control condition is verified. More sophisticated methods, such as the stochastic model Lightswitch-2002 [22] for example, have also been implemented in one dynamic energy simulation platform [23]. This comprehensive model integrates different probabilistic criteria according to the dynamic of the space occupation (arrival, intermediate or at departure).

Given the variety of control parameters and behavioral models, it is of outmost importance to assess how the control patterns for shading devices and electric lighting might affect the resulting energy performance and, consequently, to what extent they might also affect which alternative might be chosen in terms of glazing area and type, or shading device. This study thus aims to assess the impact of considering a given control model instead of another on predicted energy consumption, and to evaluate how consistent the different behavioral models currently used in dynamic simulation are in terms of outcomes and reported control criteria. Toward this end, the paper starts with a literature review of the visual comfort criteria (Section 2) and of the interaction patterns between building occupants and lighting or shading devices (Section 3). To evaluate the impact of choosing a given shading control model on determining the best-performing transparent façade option for a single-occupant office, a sensitivity study was conducted, described in Section 4 and based on EnergyPlus simulations of overall energy consumption for heating, cooling and lighting. The results of this sensitivity study are presented in Section 5 and further analyzed and discussed in Section 6.

2. Visual comfort criteria

There are numerous parameters in human psychology that influence the perception of lighting quality. Such parameters include, amongst others, mood, access to a direct view to the outdoors and the occupants' need for privacy, and cannot be objectively measured Some authors argue that, besides enabling visual comfort, "lighting quality" requirements should also comprise proper conditions for task performance and energy-efficiency considerations [24]. There also seems to be a general agreement that the most basic visual comfort requirements relate to levels of illuminance and to how light is distributed in the visual field [24–31]. This chapter presents a bibliographic review of the main physically measurable parameters that drive visual comfort, based on illuminance and luminance distributions.

2.1. Illuminance

Illuminance is the quantity underlying visual comfort requirements that is the most often referred to in lighting literature. Table 1 summarizes the recommendations found from different reviewed sources, regarding both absolute illuminance and illuminance ratios (contrast). The table shows that for office buildings, the recommendations for the minimum horizontal illuminance at the workplane vary from 200 to 600 lux for typical writing, typing and reading office tasks. For computer based tasks, however, the recommendations range is between 100 and 300 lux, significantly lower than for paper-based work. The table also presents recommendations for maximum illuminance levels on the workplane ranging between 1280 and 1800 lux, implying that above those levels glare is likely to occur. In addition, table indicates recommendations for the ratio between minimum and maximum workplane illuminance, which should be kept higher than 0.7, and ratios between horizontal illuminance of the task immediate surrounding areas and illuminance of the task between 0.2 and 0.8 meaning that illuminance of the task shall be higher than the task surroundings.

The type of tasks (computer-based or paper-based) and the source of recommendation (8 different ones) lead to variations for reference workplane illuminance of a factor of 3. Consequently the considered reference for building design and operation will significantly impact the building energy consumption – directly for the electric lighting and indirectly for the space heating and cooling.

2.2. Luminance distribution

The luminance distribution affects task visibility, comfort and perception of brightness of a space [27]. Table 2 presents a summary of the literature review addressing absolute luminances and luminance ratios. Recommendations that consider the average luminance of the visual field, wall luminance, ceiling luminance and workplane luminance were all found with highly varying recommended ranges. According to these recommendations, walls and workplane would have to have significantly lower luminances than the ceiling. The recommendations for luminance ratios take

Table 1
Illuminance recommendations for offices.

Source	Parameter	Recommendations range for comfortable spaces
[25–27,32–37]	Workplane illuminance (lux)	[100–300] – computer based tasks; [200–600] – paper based tasks; 1280–1800 – maximum values
[25,34]	$E_{Min}/E_{Max\ Workplane}$	>0.5 – accepted >0.7 – recommended
[27,29,30,34,35]	$E_{Surround}/E_{Task}$	[0.2–0.8]

Table 2
Luminance levels recommendations for offices.

Source	Parameter	Recommendations range for comfortable spaces
[30,38]	Visual field average luminance (cd/m^2)	[20–75]
[25,27,29,30]	Wall luminance (cd/m^2)	[5–179] maximum value: 1000
[25,27,35]	Ceiling luminance (cd/m^2)	[425–850] maximum value: 1000
[29,30]	Workplane luminance (cd/m^2)	[40–105]
[39,40]	Glare source luminance (cd/m^2)	Maximum value – 2500
[41,42]	Window luminance (cd/m^2)	Maximum values: [4000–6000]
[25,27,29,30,35]	$L_{Paper}/L_{urround}$	[0.33–3]
[25,27]	$L_{VDT}/L_{urround}$	[0.33–3]

into consideration the ratios of paper or VDT luminance and surrounding area luminance, with recommended ratios of at most 1:3 between the task and the immediate surrounding area luminance.

A bibliographic review regarding the compatibility of recommendations referring to luminance found no results. Significant discrepancies might be expected regarding the design options and the energy consumption that would result from the adoption of different recommendations of luminance levels.

One of the undesired effects of inadequate luminance distribution is glare, a visual phenomenon that can be caused by too much brightness or too high luminance ratios in the field of vision. Several indices and metric have been investigated to try to characterize the tendency of given indoor conditions to cause this sensation. The Visual Comfort Probability (VCP) [43], predicts the percentage of population that will accept a given lighting condition as comfortable based on electric lighting. An alternative was developed by the International Commission on illumination (CIE) to produce a consensus glare calculation system and named the Unified Glare Rating (UGR). Its main enhancement compared to VCP was the simpler calculation procedure, which made it ultimately substitute the VCP [44].

For daylighting, which involves wide luminance ranges and potential glare sources, several parameters can be found. One of the simplest is the maximum window luminance, as reported by Platzer [41] and also adopted by EN 14501 [42]. Some specific daylight glare indices were and are still being developed. The daylight glare index (DGI), commonly referred to in the calculation of daylight discomfort glare [45], is based on a mathematical formulation that uses the glare source luminance (average window luminance), the solid angle, the background luminance (average luminance of the field of view, excluding glare source) and the position index. It indicates the degree of discomfort glare due to daylight. Some limitations in its application were identified for the prediction of glare under real sky conditions and for situations where the glare source is non-uniform or fills approximately the whole field of view [39,44,46]. As a result Nazzal [47,48] proposed changes to the calculation of the DGI, introducing the new daylight glare index (DGI$_N$), whose main enhancement consisted of increased accuracy relatively to the DGI formulation. Its adequacy to predict glare sensation has not yet been validated with other independent studies. Another recent index characterizing discomfort glare is the daylight glare probability (DGP) [49]. It intends to express the percentage of people experiencing glare in a given visual condition and is based on the vertical eye illuminance, the glare sources luminance, the solid angle and the position index. It was developed considering several daylighting conditions, analyzing the response of 70 subjects in two different locations, Copenhagen (Denmark) and Freiburg (Germany). The evaluation of experimental results and users response has shown a good correlation between DGP and discomfort glare as subjectively assessed by occupants, better than any of the previously mentioned indices [49]. A notable development is DGP's strong dependency on vertical eye illuminance, much stronger than other tested functions like window luminance, DGI and the CIE glare index [9]. The consideration of the vertical illuminance as a measure of the eye adaptation level represents the main difference of DGP relatively to UGR, DGI and DGI$_N$, which consider the background luminance as adaptation parameter, overcoming the difficulty of those indexes to predict glare from large sources.

Table 3 summarizes the main parameters found to characterize glare and the respective recommended ranges for visual comfort. While VCP and UGR were developed for evaluating the level of comfort of indoor environments lit by artificial lighting, DGI and DGP were developed to express the visual comfort under daylight conditions. The consideration of glare indexes during building design and/or operation directly influence the choice of the lamps, daylight systems or indoor environment features and the resulting overall energy consumption.

2.3. Other parameters related to lighting quality

Beyond illuminance and luminance distribution considerations, certain lighting qualities that contribute to a space overall lighting performance in terms of occupants satisfaction might also influence visual comfort even though they are not as easy to measure objectively. These would typically include light directionality, its spectral distribution and access to a direct view. Some authors [50–52] also argue that since light "affects the appearance of three-dimensional objects" [51], the potential of lighting to produce shadows and

Table 3
Main parameters to characterize glare and the respective recommended ranges for visual comfort.

Source	Parameter	Recommendations range for comfortable spaces
[27]	Visual comfort probability (VCP)	>70 – recommended value; >80 – minimizing discomfort glare;
[34,35,39]	Unified glare rating (UGR)	19 – maximum (offices); >22 – uncomfortable;
[39]	Daylight glare index (DGI)	≤22 – comfortable; 24–26 – uncomfortable ≥28 – intolerable
[9,49]	Daylight glare probability (DGP) (DGP limit value – 95% of office-time weaker than the perceived glare sensation)	≤0.35 – imperceptible (best class – A) ≤0.40 – perceptible (good class – B) ≤0.45 – disturbing (reasonable class – C) >0.45 – intolerable

highlight patterns in a three-dimensional space should be acknowledged as an important aspect of light distribution assessment.

In terms of color and appearance, it is well known that while daylight's spectrum guarantees excellent color rendering [53], the use of some chemical coatings on glazings with low-emissivity or solar protection performance will both reduce the amount of transmitted daylight and modify its spectral distribution. A literature review presented by Dubois [54] refers that, in general, the spectral properties of a glazing directly influences the acceptance of the resulting indoor environment, seeming that occupants tend to prefer the daylight resulting from bronze glazing over the daylight resulting from neutral and blue glazings [55]

Finally, access to a direct view of the outdoor environment has been reported as an important contributor to the visual comfort perception in a room [42,56,57]. Occupants also seem to prefer a natural rather than a built or urban view [58]. Recently, further studies and field work have been conducted to better understand the role of the view out (with varying degrees of 'interest') in a space's visual perception and potential for visual discomfort [59,57] and tend to report a positive influence of the view out on perceived visual discomfort. Other tangible variables that are also referred to in the literature as influential in visual comfort perception include the flicker rate of artificial light sources, the type of lighting system (direct versus indirect) and the type of lighting control [27,30].

There is a large range of criteria that are indicated in the literature that affirm to ensure visual comfort or representing occupants preferences in office buildings. Significant differences are found among the criteria, which makes also expect considerable differences in subsequent choices of building design options or in evaluating building energy consumption performance.

3. Conditions that cause of manual operation of shading devices and electric lighting

Several reasons have been indicated as potentially motivating factors in the control of shading devices or electric lighting by occupants of office buildings. This section summarizes the conditions that seem to cause a manual operation of shading devices and electric lighting as indicated in the literature.

Tables 4 and 5 identify the criteria that are used to model occupants operation of shading devices (Table 4) or electric lighting (Table 5). The literature review revealed that such criteria were usually based on physical parameters that were either measurable or computable, and involving a strong connection between lighting quality and the stimulus to adjust shading or electric lighting. Some of the criteria straightforwardly use parameters described in Section 2 based on illuminance and/or luminance distributions, while others relate to weather conditions, based on solar radiation and external illuminance.

The occupants' behavior patterns were identified from both field monitoring in buildings and laboratory data. However, most of the reported criteria were based on a limited number of offices in specific locations and in restricted monitoring periods. The use of such criteria therefore requires the exact assessment conditions to be taken into account, making generalization difficult. Most of the criteria indicated in Tables 4 and 5 are static triggering values, with fixed frontier values that characterize a deterministic model. A different approach has also been tried by some authors where occupants' actions are instead characterized by a probability of occurrence [2,3,6,14].

According to Table 4, office building occupants will activate or deactivate the shadings based on three different types of criteria:

(i) quantity of daylight (illuminance) that falls on the workplane;
(ii) visual discomfort related to glare, accounted indirectly by window luminances, transmitted solar radiation or directly by daylight glare indexes;
(iii) direct solar radiation, which can create both thermal and visual discomfort.

There is no agreement about which behavioral model or control pattern best predicts occupants actions for each building design and weather conditions, Furthermore, many are formulated in different primary parameters, which makes it difficult to assess their compatibility. Nevertheless, this review suggests the following:

- Solar radiation has been the most cited parameter driving shading control.
- Among the different sources, solar radiation is expressed in different ways, such as direct or global solar radiation, incident or transmitted solar radiation, beam or vertical solar radiation. It is very difficult to assess the compatibility of the different criteria, especially because each criteria was developed under specific research conditions.
- The criteria based on visual discomfort have few citations, probably denoting that the methods to assess glare conditions are insufficiently known or trusted by the academic community not specific to visual comfort studies.
- Activating the shading devices is more dependent of the environmental conditions than deactivating the shadings. The number of studies referring the criteria for deactivating shading devices is very low.
- The majority of criteria indicate deterministic threshold parameters; however the more recent studies report probabilistic correlations for the shading positions adjustments.

As far as the interaction between building occupants and electric lighting is concerned, it has been the object of study for decades with some widely accepted patterns [3,61]. Table 5 presents a review of the criteria for manual control of electric lighting as reported in the literature. Two different patterns can be observed. In the first one, the electric lighting is switched-on during the hours when the office is occupied. According to this model, during the occupation period people rarely switch-off the lights once daylight illuminance levels override the set point for illuminance, and most of the time occupants do not have the perception of the luminaires' state [3]. In a second reported model, the lights are switched-on when the daylight illuminance level is not sufficient to perform tasks. Generally the electric lighting is switched-off when the occupants leave the office.

By observing that the operation of electric lighting is strongly related to illuminance and luminance levels in the rooms, it is reasonable to assume that there is also an indirect connection between the actuation of shading devices and electric lighting. The adjustment of the shadings state (increase of opacity) to control glare will result in a high probability of switching on the lights (if before switched off). Logic would indicate a low chance of the inverse happening i.e. deactivating shading and consequently switch off electrical lighting, but no references were found about this specific behavior.

The manual operation of shading devices and electric lighting has been object of several studies and different conditions were reported as possible options to model the behavior of office building occupants. Twenty models or criteria were found that relate to the manual operation of shading devices and eight models or criteria that relate to the manual operation of electric lighting, with a large diversity of control approaches (control parameters, thresholds, type of criteria and applicability). The indicated conditions are not necessarily compatible amongst each other and might

Table 4
Review of the criteria for manual control of shading devices in office buildings.

Driving parameter	Source	Criteria for adjustment of the shading position	Action		Development context
			Opening	Closing	
Indoor illuminance	[5,37]	Shade actuated if $E_{Workplane\ Daylight}$ higher than 1800 lux		×	Survey of 16 office buildings. U.K.
	[2]	*Actions on arrival (lower blinds)* Probability of window blind closing as a function of indoor illuminance and lower unshaded window fraction (combined 5000 lux and 100% result in a probability of action of 81%)		×	Monitoring of 14 one or two-person offices during 7 years. Switzerland
	[2]	*Actions on arrival (lower blinds)* Probability of window blind opening as a function of indoor illuminance and lower unshaded window fraction (combined 500 lux and 0% result in a probability of action of 50%).	×		Monitoring of 14 one or two-person offices during 7 years. Switzerland
	[2]	*Actions during the presence and at departure (lower blinds)* Probability of window blind closing as a function of indoor illuminance and lower unshaded window fraction (combined 5000 lux and 100% result in a probability of action of 19%)		×	Monitoring of 14 one or two-person offices during 7 years. Switzerland
	[2]	*Actions during the presence and at departure (lower blinds)* Probability of window blind opening as a function of indoor illuminance and lower unshaded window fraction (combined 500 lux and 0% result in a probability of action of 16%)	×		Monitoring of 14 one or two-person offices during 7 years. Switzerland.
Luminance	[25]	Inferred that shading is actuated if any $L_{Visual\ field}$ higher than 1000 cd/m^2		×	Undetermined
	[41]	Inferred that shading is actuated if L $_{Window}$ higher than 5000 cd/m^2		×	Undetermined
	[6]	*Actions on arrival* Probability of window blind closing as a function of maximum window luminance (4466 cd/m^2 for a probability of action of 50%), background luminance (225 cd/m^2 for a probability of action of 50%), and average window luminance (890 cd/m^2 for a probability of action of 50%),		×	Survey of 2 office buildings offices during 5 months. California, U.S.
	[7]	Shading actuated if L_{Window} higher than 1800 cd/m^2		×	Monitoring of 8 one person offices during 7 months. France
Glare indexes	[8]	Shading actuated if DGI higher than 20		×	undetermined
	[39]	Inferred that shading is actuated if DGI higher than 24		×	undetermined
	[9,49]	Shading actuated if DGP higher than 40%		×	Experimental study and occupants survey (70subjects). Denmark and Germany
Solar radiation and external illuminance	[13]	Shade actuated if intensity of direct normal solar radiation hitting the occupants higher than 233 W/m^2		×	Undetermined
	[8]	Shade actuated if transmitted direct solar radiation (through the transparent façade) higher than 94.5 W/m^2		×	Undetermined
	[10,17]	Shading actuated if vertical solar irradiation higher than 300 W/m^2		×	Undetermined
	[11]	Shading actuated if the direct solar radiation that hits the workplace higher than 50 W/m^2 (considering a specified dept into the room of 1 m)		×	Monitoring and occupants survey of 4 office buildings during 3 weeks. Japan
	[4]	Shading actuated if direct sunlight higher than 50 W/m^2 and solar gains higher than 50 klux (450 W/m^2)		×	Monitoring of 10 one and two-person offices during 9 months. Germany
	[4]	Shading actuated if illuminance on external façade higher than 25klux	×		Monitoring of 10 one and two -person offices during 9 months. Germany
	[6]	*Actions on arrival* Probability of window blind closing as a function of transmitted vertical solar radiation (13 W/m^2 for a probability of action of 50%)		×	Measurements and occupants survey of 2 office buildings offices during 5 months. California, U.S.

Table 4 (*Continued*)

Driving parameter	Source	Criteria for adjustment of the shading position	Action		Development context
			Opening	Closing	
	[60]	Mean shade deployment degree (m.s.d.d.) as a function of incident vertical solar irradiation (South 250 W/m^2 m.s.d.d.=75%; North 250 W/m^2 m.s.d.d.=13%; South-west and south-east 250 W/m^2 m.s.d.d.=62%; North-west and north-east 250 W/m^2 m.s.d.d.=19%; West and east 250 W/m^2 m.s.d.d.=50%)	×	×	Monitoring of 5 office buildings (163 workplaces) during 9–14 months. Austria

significantly impact the overall energy consumption of office buildings when used in integrated building simulation.

4. Sensitivity analysis for an office case study

The literature review from the previous sections showed that there are different control models of how people interact with shading devices and with electric lighting. These interactions in turn influence building performance in terms of their energy demand for heating, cooling and artificial lighting. It is therefore important to assess how the choices of behavioral models might influence the forecasted energy demand. It is also important to assess whether the differences in energy consumption prediction resulting from the selection of a behavioral model have an impact on the subsequent ranking of design alternatives for the transparent façade elements (e.g. the glazing type, the shading device or even the area of transparent surface). If this is the case, then increasing the robustness of existing behavioral models – or developing a more robust method to choose amongst the models – would become a priority for reliable energy simulations.

So as to assess the impact of the behavioral model choice (regarding interaction with shading devices and electric lights) on the energy performance of buildings, a detailed study was performed taking as reference a single-occupant office room located in Porto, Portugal. Porto is located at the latitude of 41°N and has an European Atlantic Climate, with 1610 heating degree-days at base temperature of 20 °C. The room (Fig. 1) was modeled in whole-building simulation software, and different transparent façade design options were tested. A more detailed description of the building and room are presented in Section 4.1.

Fig. 2 summarizes the framework of the conducted simulations. This framework included:Three scenarios regarding the result of climate and building characteristics: a heating-dominated scenario, a cooling-dominated scenario and one with balanced heating and cooling. The differentiation was achieved by increasing the level of thermal insulation of the envelope (to achieve a cooling-dominated scenario) or by lowering the air temperature of the climate file (to achieve a heating-dominated scenario);For each of the scenarios described in (i), the analysis of four options regarding the choice of glazing, four options regarding the shading devices, and four options regarding the area of transparent façade;The energy demand with each of the glazing, shading or window areas described in (ii) was calculated for 11 behavioral models of the interaction between the occupants and the shading devices.

Table 5
Criteria of manual control of electric lighting in office buildings.

Driving parameter	Author	Criteria for adjustment of the electric lighting state	Action		Development context
			Switching-on	Switching-off	
Illuminance	[61]	Probability of lights being switched on function of external total illuminance (in a multi-person office) (36 klux for a probability of action of 50%)	×		Monitoring of 3 multi-person offices during 6 months. U.K.
	[3]	*Actions on arrival* Probability of lights being switched on as a function of indoor illuminance (67 lux for a probability of action of 50%)	×		Monitoring of 3 multi-person offices during 6 months. U.K.
	[4]	*Actions on arrival* Probability of lights being switched on as a function of indoor illuminance (170 lux for a probability of action of 2%)	×		Monitoring of 10 one or two-person offices during 9 months. Germany
	[4]	*Actions during the presence* Probability of lights being switched on as a function of indoor illuminance (67 lux for a probability of action of 50%)	×		Monitoring of 10 one or two-person offices during 9 months. Germany
Luminance	[27]	Inferred that electric lighting state is adjusted if $L_{Ceiling}$ higher than 850 cd/m^2		×	Occupants preferences
	[35]	Inferred that electric lighting state is adjusted if $L_{Ceiling}$ higher than 500 cd/m^2		×	Occupants preferences
Period of absence	[14]	Probability of lights being manually switched off function of length of occupancy absence from the workstation (range 1–2 h for a probability of action of 38%)		×	Monitoring of 63 one person offices during 11 months. Winscosin, U.S.
	[12,60]	Probability of lights being manually switched off function of length of occupancy absence from the workstation (125 min for a probability of action of 50%)		×	Monitoring of 5 office buildings (163 workplaces) during 9 to 14 months. Austria

Fig. 1. Case study – single office room.

For each combination of scenario and design alternative, the electric lighting and space heating and cooling needs were calculated through dynamic building simulation, using the Porto's hourly weather data file. In each of the simulations electric lighting was considered to be controlled with an ideal dimming complementary to natural lighting, in order to ensure 500 lux on the workplane during the occupied period.

4.1. Geometry and envelope

The office room is 5.3 m long and 3.0 m wide, resulting in a floor area of 16 m^2. The room is daylit by a south oriented window of 5.5 m^2, which fills about 65% of the office south façade. The only elements of the office envelope that contact with the outdoors are the south façade (8.5 m^2). The external walls have a *U*-value of 0.67 $W/m^2\,^\circ C$. All the other elements of the office envelope in contact with other office rooms were assumed to be at the same indoor environmental conditions. The window is shaded by external Venetian blinds. The room occupancy was defined as 1 person from 9 to 13 h and from 14 to 19 h, the artificial lights electric power as 10 W/m^2 from 9 to 19 h, the office equipments electric power as 10 W/m^2 from 9 to 19 h, and the fresh air ventilation rate as 1 ach from 9 to 19 h and 0.5 ach from 0 to 9 h and from 19 to 24 h.

The assessment of the office overall energy consumption (for lighting, heating and cooling) was performed considering different design alternatives for the transparent façade: glazing types, window to wall ratios and shading devices.

As far as glazings are concerned, the range of analyzed alternatives consisted of four different double layer glazing windows (6 mm-12 mm-6 mm), whose main properties are shown in Table 6. These exhibit similar coefficients of heat transmission but different optical values, covering the overall range of existing glazing optical characteristics, from a dark solar control glazing (G1) to a very clear glazings (G4) [62]. It was considered that all of these glazings have very high color rendering indexes and therefore, neutral impact on color perception.

Four different values of window to wall ratio (WWR – percentage of the exterior wall area which is made of window) were tested, 20%, 40%, 65% and 90%, always keeping the center of window at the occupants view level. Table 9 shows the properties of the considered WWR alternatives.

The properties of the four options for the external venetian blinds considered for this study were taken from the calculation tool WIS [63] and are presented in Table 8. Similarly to the glazings, the four shading device options were selected based on their transmittance values.

As mentioned in the introduction of this section, a sensitivity analysis of Tables 6–8 was performed three times: first in a scenario where the annual cooling demand is significantly higher that the heating demand, second with two demands that are of the same order of magnitude and third with a cooling demand significantly lower than the heating demand. The cooling-dominated scenario corresponds to the "as built" in Porto, considering one exterior wall, South-oriented, with an *U*-value of 0.48 $W/(m^2\,^\circ C)$. The transformation toward "balanced heating and cooling" was achieved by considering walls and roof as external (*U*-values of 0.48 $W/(m^2\,^\circ C)$ and 0.27 $W/(m^2\,^\circ C)$, respectively), which increased the heat losses toward outdoors; and finally, to achieve a heating-dominated scenario, the envelope of the balanced heating and cooling scenario was considered however the climate file was changed by arithmetically removing 8 °C from the outdoor temperature in the climate file for all hours of the year. This virtual climate file option was considered preferable to changing the climate location, as the latter would affect also the daylighting availability and consequently decrease the comparability of the results.

4.2. Behavioral models/control strategies of the shading devices

The main objective of this work is to assess the impact that behavioral models and associated control patterns for shading devices have in terms of energy demand for heating, cooling and electric lighting. Therefore, following the review presented in Sections 2 and 3, a comprehensive set of behavioral models was selected to be subjected to a sensitivity analysis. The set is essentially the one already presented in Table 4, plus four steady-state strategies. They are all summarized in Table 9 as a single list.

The strategies S0 (blinds totally inactive) and S1 (blinds totally active) are not representative of real patterns of blinds control but were considered as limit conditions.

S2 and S3 are the strategies most often considered in practice by building designers and consultants when assessing the energy performance of buildings. They sometimes are imposed by the calculation methods adopted by national regulations [15].

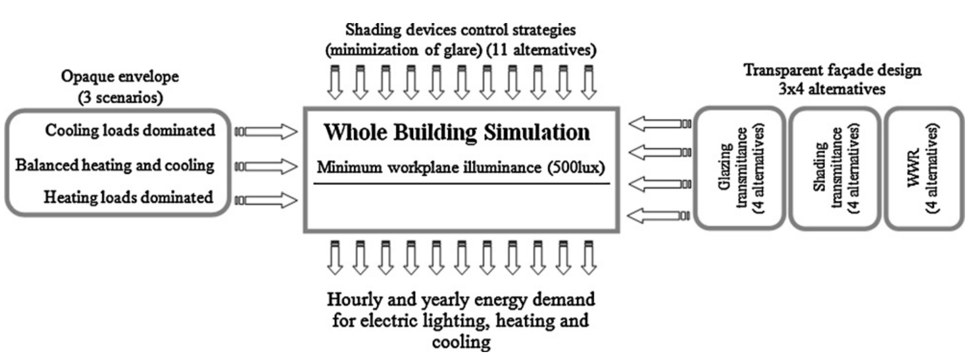

Fig. 2. Summary of the framework of simulations.

Table 6
Transparent façade – glazing types alternatives.

	Glazing properties				Shading device	WWR
	U-value W/(m^2 °C)	g-Value (%)	T_{Sol} (%)	T_{Vis} (%)		
G1	1.57	20	3	6	Shad3 (T_{Sol} = 24.0%; T_{Vis} = 24.9%)	WWR3 (65%)
G2	1.57	30	15	24		
G3	1.57	51	41	43		
G4	1.58	75	63	79		

Table 7
Transparent façade – WWR alternatives.

	WWR (%)	Glazing type	Shading device
WWR1	20	G3 (T_{Sol} = 41.0%, T_{Vis} = 42.0%)	Shad3 (T_{Sol} = 24.0%; T_{Vis} = 24.9%)
WWR2	40		
WWR3	65		
WWR4	90		

The strategies S4, S5, S6 and S7 are based on the assumptions that occupants activate external blinds each time they are visually uncomfortable, and that they turn the blinds inactive again as soon as the occupants are comfortable without the action of the blinds. Two different threshold values for the DGI were considered (16 and 22). Recognizing that DGI is highly dependent on the occupant view angle, two different positions were considered for the occupant: a standard occupant position that would represent a view angle parallel to the window (0°) and a second one which considers the occupant slightly turned toward the window (view angle of 20° with the window plane).

The strategies S8 and S9 make use of the vertical solar radiation transmitted through the window to adjust blinds positions. The value of beam (direct normal) plus the diffuse radiation is calculated for each simulation time-step and the blind is fully lowered if the transmitted solar radiation through the window (without the effect of the shading device) is higher than a specified solar radiation value (100 W/m^2 in S8 and 200 W/m^2 in S9). For each glazing type the glazing solar transmittance was considered to find the incident solar radiation that shall be used to trigger the blind position.

The strategies S10 and S11 rely on the user behavioral control model Lightswitch [22,64]. This model is integrated in DAYSIM [65]. The two different types of user behavior were tested: the active (S10) and the passive (S11). They both will partly close the shading devices during the day to avoid direct sunlight higher than 50 W/m^2 impinging the working space. Once closed, they will remain in that state. The main difference between both types is that the active type fully opens the shading devices when arriving in the morning, while the passive type does not do this.

4.3. Estimation of the overall energy consumption

All simulations were performed with the EnergyPlus building simulation software [19]. It allows for the direct implementation of the control strategies S0 to S9. For strategies S10 and S11, the DAYSIM [65] output text files (hourly values of indoor illuminance, electric lighting and shading devices state) were used as inputs to EnergyPlus to specify the state of the blind at each hour of the year, thus ensuring the connection of both algorithms. The thermal part was treated by EnergyPlus alone.

All simulations were performed with an ideal dimming strategy to control electric lighting to prevent possible overlapping between manual occupants' models to control electric lighting and models to control shading devices. This means that the light power of the office room is continuously adjusted by a virtual real-time ideal-dimming system, which reduces the electric power proportionally to the amount of incident daylight to guarantee a minimum of 500 lux on of the workplane, positioned 2 m away from the window. The calculation of the daylight contribution is based on Daylight Factors for a standard overcast sky and on indoor and outdoor illuminance ration for clear sky conditions with 20 different representative sun positions of one indoor reference point [66,67]. The models using the control strategies S10 and S11 use the indoor illuminance calculated by DAYSIM, as referred previously. DAYSIM has an integrated RADIANCE algorithm coupled with a daylight coefficient approach to estimate daylight illuminances [65].

For each simulation, the total annual energy consumption for electric lighting, ambient heating and ambient cooling was evaluated based on the building design options, the control strategies and the boundary conditions described previously. To estimate the final energy consumption for space heating and cooling the indoor temperature was assumed to be controlled during office room working hours (9–19 h), and kept at a minimum of 20 °C during the heating season and a maximum of 24 °C during the cooling season. The energy consumption is computed in the form of electricity, assuming that the heating and cooling are provided by a reversible heat pump system with a seasonal COP of 4 and a EER of 3, respectively.

5. Results

5.1. Cooling dominated scenario

In the context of the cooling-dominated scenario, Fig. 3 shows the annual energy consumption of the office room, for the four glazing alternatives G1 to G4 presented earlier in Table 6, under each

Table 8
Transparent façade – shading devices alternatives.

	Shading device properties		Glazing type	WWR
	T_{Sol} (%)	T_{Vis} (%)		
Shad1 (venetian blinds)	11.9	11.9	G3 (T_{Sol} = 41%, T_{Vis} = 42%)	WWR3 (65%)
Shad2 (venetian blinds)	16.8	17.7		
Shad3 (venetian blinds)	24.0	24.9		
Shad4 (venetian blinds)	29.5	31.7		

Table 9
Behavioral models/Shading devices control strategies to be considered in the sensitivity analysis.

S0	No shading (shading fully open all year round)
S1	Shading is 100% active from January to December
S2	Shading is 70% active from April to September
S3	Shading is 100% active from April to September
S4	Shading is active if DGI >20 (GI > 16), 0° (view direction parallel to window)
S5	Shading is active if DGI >20 (GI > 16), 20° (view direction 20° toward window)
S6	Shading is active if DGI >24 (GI > 22), 0° (view direction parallel to window)
S7	Shading is active if DGI >24 (GI > 22), 20° (view direction 20° toward window)
S8	Shading is active if transmitted vertical beam plus diffuse solar radiation (SRTr) >100 W/m2
S9	Shading is active if SRtr >200 W/m2
S10	Shading is active if direct sunlight that hits the workplane >50 W/m2, active user (Lightswitch)
S11	Shading is active if direct sunlight that hits the workplane >50 W/m2, passive user (Lightswitch)

of the 12 shading control strategies S0 to S11 described in Table 9. The energy consumption for each scenario is presented in kWh per year per m^2 of office floor area (Fig. 4).

Fig. 5 shows the results for the four shading alternatives presented in Table 7, while Fig. 6 shows the results for the four alternatives of WWR described in Table 8.

In cooling-dominated scenario, results show that different behavioral models result in different choices of a "best design alternative". The differences are most noticeable for the choice of glazing alternatives and WWR alternatives, higher variations of overall energy consumption are also observed when compared to the energy consumption associated with shading alternatives. This is somewhat natural, since the differences amongst the glazing and WWR values are also bigger than for shading (see Table 7). The shadings control strategies S0 and S1 are indicated as references, to assist the analysis of strategies S2 to S11. Overall results present a considerable dispersion in terms of energy consumption, with significant differences both between design alternatives and between the twelve shading control strategies. While the ranking of the alternatives is generally not significantly influenced by the change of control strategy, there are exceptions for strategies S1, S8 and S11, which all lead to shadings being active during most if not all of the time. Furthermore, the lower transmittances and wall areas are less sensitive to changes in control strategy. The two variants of the Lightswitch behavioral model produce significant ranking variations. These are justified by the fundamental differences in the algorithms: with the passive user mode, the shadings are fully deployed almost always throughout the year.

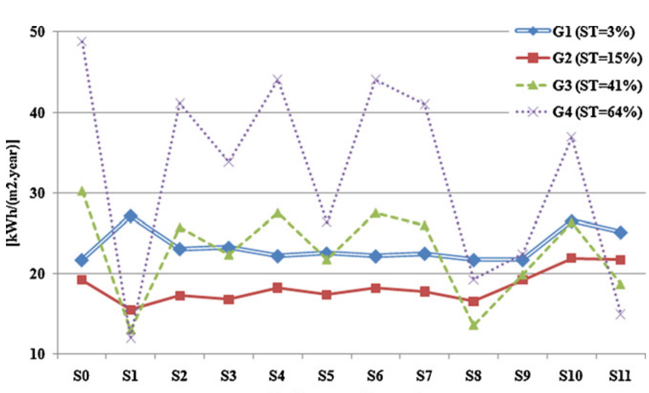

Fig. 3. Overall energy consumption for the four glazing alternatives in each of the 12 control strategies.

5.2. Heating dominated scenario

For the heating-dominated scenario, Fig. 7 shows the annual energy consumption of the office room, for the four glazing alternatives G1 to G4 under each of the twelve shading control strategies S0 to S11. Fig. 8 shows the results for the four shading alternatives presented in Table 7, while Fig. 9 shows the results for the four alternatives of WWR.

In this heating-dominated scenario, the ranking of design alternatives remains nearly constant across the different shading devices control strategies. The exceptions are the parametric studies related to the glazing and those related to the shading transmittance in those cases where the Lightswitch-active user model leads to some ranking inversion. The relatively small influence of the control strategies in this scenario is also confirmed by the fact that the energy consumption of each design alternative tends to be similar across the different control strategies. An explanation for this is the fact that the decrease in electric lighting needs decreases is partially offset by an increased need for heating.

5.3. Balanced heating and cooling scenario

The annual energy consumption of the office room for the case when heating and cooling energy needs are comparable, is shown in Fig. 10 for the four glazing alternatives. Fig. 11 shows the results for the four shading alternatives and Fig. 12 shows the results for the four WWR alternatives.

In this scenario, a reasonable number of ranking inversions occur across control strategies. The strategies S9 and S10 imply ranking variations if compared with the ranking resulting from the DGI based criteria (S4 to S7) and the Lightswitch criteria (S10), but are similar to the ranking of the seasonal-based strategies (S2 and S3). As in the previous scenarios, the influence of the control strategies on the energy consumption is more noticeable in the simulation of the glazing transmittance and window to wall ratio alternatives.

6. Results analysis

The main purpose of this case study is to assess the impact of the shadings control strategy (which supposedly mimics the human behavior) on the selection of transparent façade alternatives, when using the overall consumption of final energy for heating, cooling and lighting as the decision criteria. The results discussed in Section 5 do show that shading control strategies influence the choice of the best design alternative.

In order to analyze in a systematic way how the energy results and design options are affected by the control strategies and behavioral model, a set of indicators were computed (Table 10):Best alternative: percentage of occurrences (control strategies) in which the design alternative leads to the lowest energy consumption among the alternatives analyzed;Average ranking: average position index of each alterative considering all the control strategies (where, for each control strategy, the position index is 1 for the alternative which results in the lowest energy consumption and 4 the alternative which results in the highest energy consumption);Ranking ratio (max/min): ratio between the highest and lowest position index of each design alternative in the range of control strategies analyzed. A ranking ratio of 4.0 therefore means that the alternative has at least one control strategy in which it is the best design option and at least one control strategy in which is the worst option. A ranking ratio of 1.0 indicates that the ranking position of the alternative is constant through all the control strategies (regardless of ranking position).

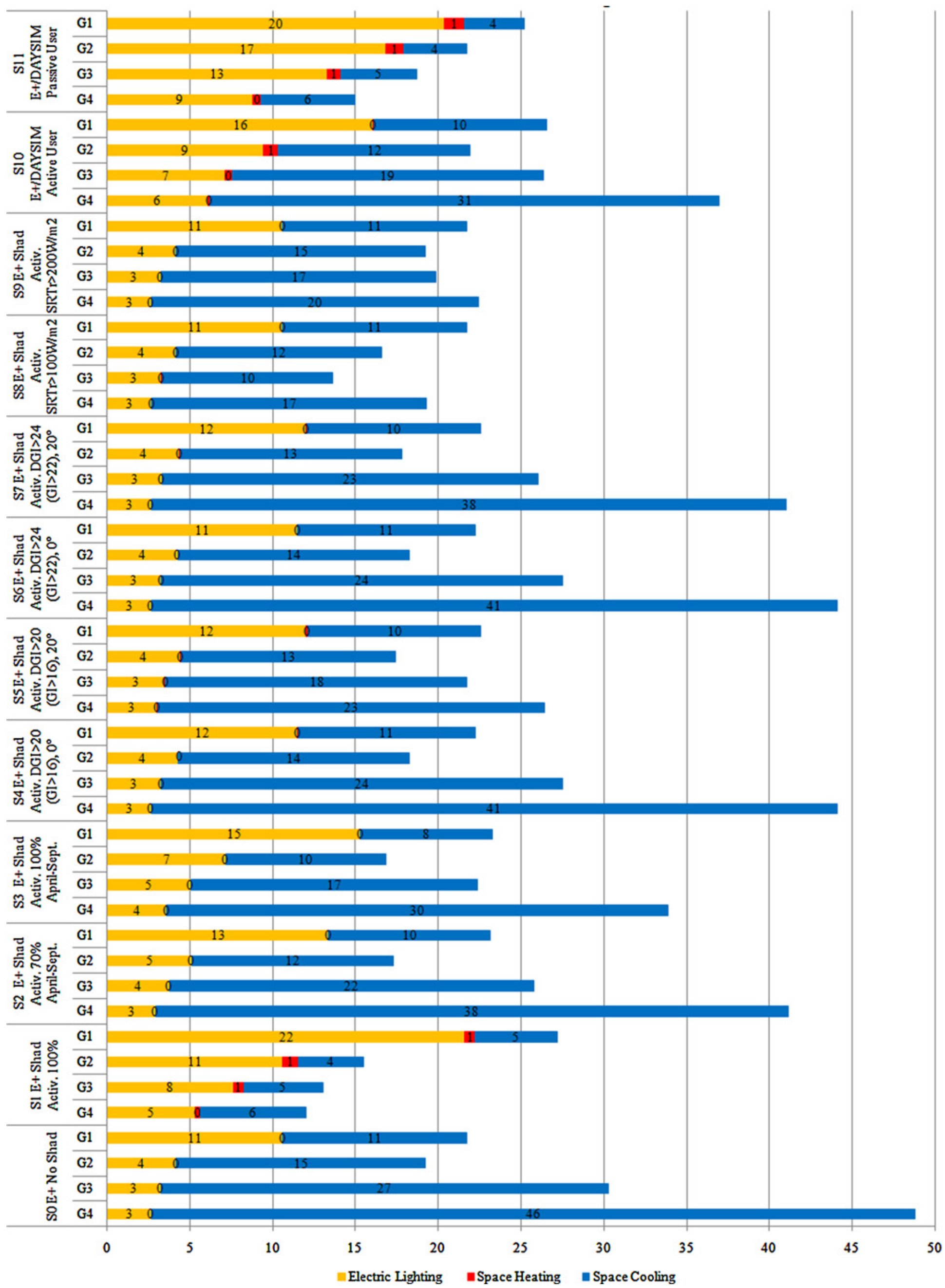

Fig. 4. Yearly energy consumption disaggregation for the four glazing transmittance alternatives.

Table 10 shows the indicators computed for each transparent envelope design alternative (glazing, shading and window-to-wall ratio). The calculation of the indicators did not take into consideration the shadings control strategies S0 and S1, since those strategies consider a permanent state of the shadings during all the year (they were studied for reference comparison only).

The indicators shown in Table 10 confirm that the energy-based merit of a given design alternative varies considerably with the control strategy assumed in the simulation. From the 9 sets of case-studies analyzed, only in one case (variation of the window-to-wall ratio in the heating dominated scenario) was there a design alternative (WWR4) which was always the best under any of the control strategies considered (S2 to S11). Furthermore, there is a significant number of design alternatives that have a ranking ratio of 4.0, meaning that they are considered the best with some control strategy(ies) and the worst with some other control strategy(ies). The table however also reveals that the dispersion is much more significant in the "balanced heating and cooling" scenario than in the "cooling dominated scenario" and especially than in the "heating dominated scenario". In this latter one, the identification of the best alternative is almost consensual, with at least 90% of the control strategies leading to the same choice of best alternative. In the "balanced heating and cooling" scenario however there is a case in which the best alternative is not recognized as such by as much as 40% of the control strategies.

The fact that the use of different control strategies may lead to the choice of different design solutions is inconvenient from a practical point of view. It may also mean that many design solutions chosen today as energy efficient may in fact not be so. This justifies the need for further research in this area, which may lead

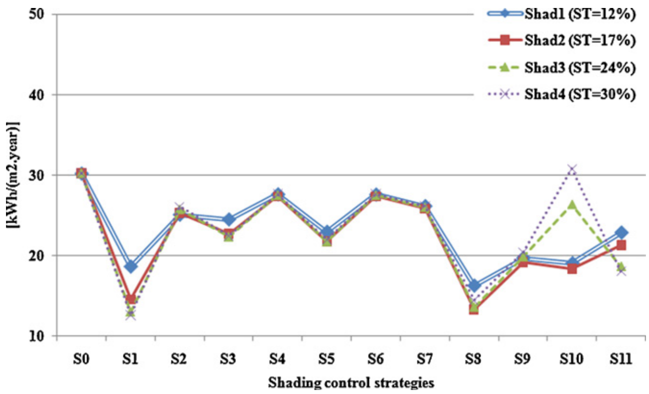

Fig. 5. Overall energy consumption for the four shading transmittance alternatives in each of the 12 control strategies.

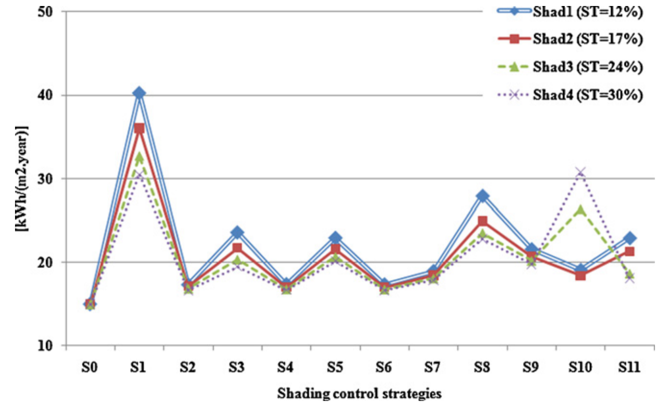

Fig. 8. Overall energy consumption for the four shading transmittance alternatives in each of the 12 control strategies.

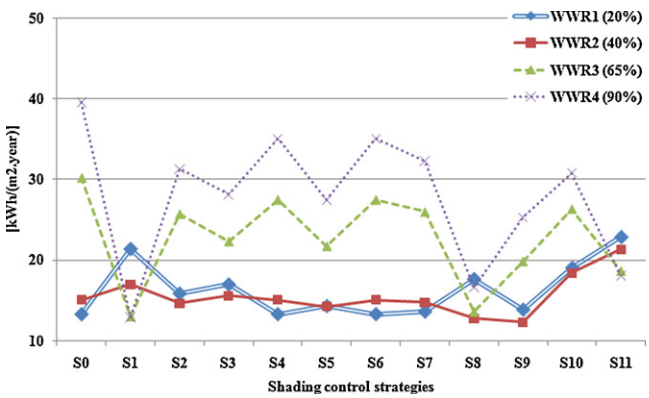

Fig. 6. Overall energy consumption for the four window to wall ratio alternatives in each of the 12 control strategies.

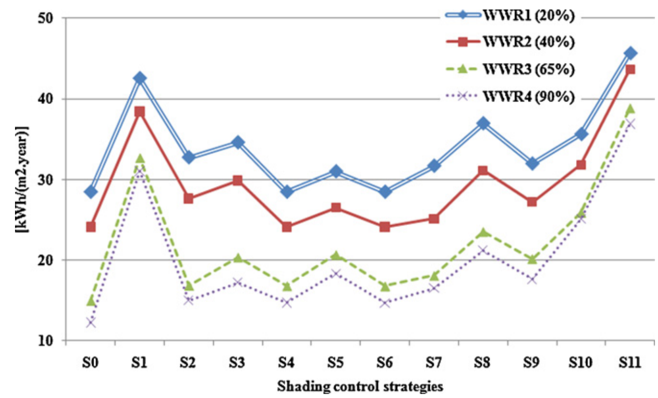

Fig. 9. Overall energy consumption for the four window to wall ratio alternatives in each of the control strategies.

to behavior models with higher statistical significance so as to be widely acceptable as representative of occupants' behavior.

While such models are not available, and given that there is no scientifically solid indication that any of the behavioral models or control strategies is clearly better than the others, a possible solution recommendable from a methodological point of view would be to consider all the control strategies and choose the design alternative that ranks best according to the average. A variant of this method would be to choose a design alternative that ranks well and has a low ranking ratio (meaning that even if not guaranteeing the best performance, it would never lead to poor performance).

However, in the regular practice of building design, it is not convenient either – if feasible at all – to simulate the building with different design solutions and different control strategies to perform a choice analysis after that. In fact, as referred to in Section 1, considering one dynamic control pattern is already a procedure on the advanced side of the building design practice. Therefore, a search for the most reliable control strategy is required, i.e. are which would be most likely to lead to the choice of the same design alternative as the procedure based on the "best according to the average of the control strategies" would. This would indeed allow to simulate with just one control strategy instead of the nine control strategies initially considered. Table 11 provides a list of "the best according to the average" and "the best according to each individual control strategy". The last line of the table also shows the

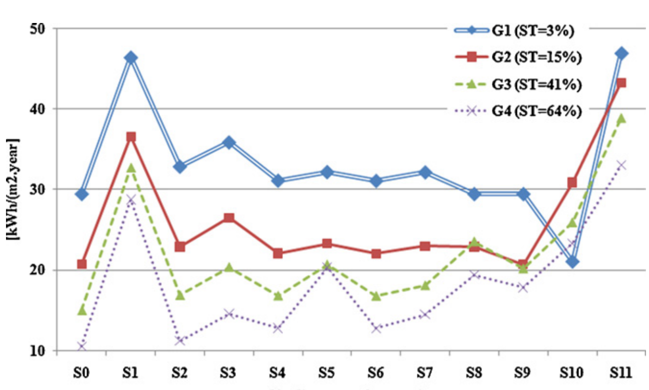

Fig. 7. Overall energy consumption for the four glazing transmittance alternatives in each of the 12 control strategies.

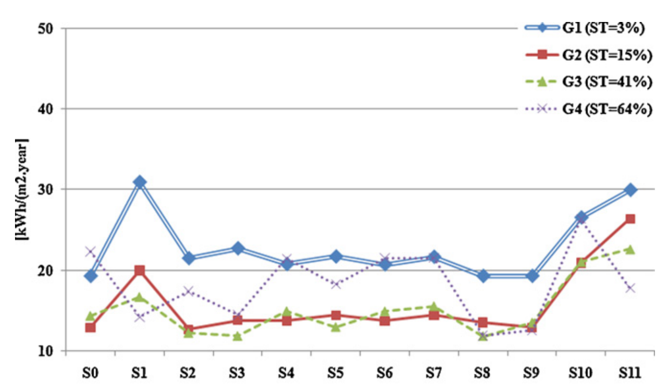

Fig. 10. Overall energy consumption for the four glazing transmittance alternatives in each of the control strategies alternatives.

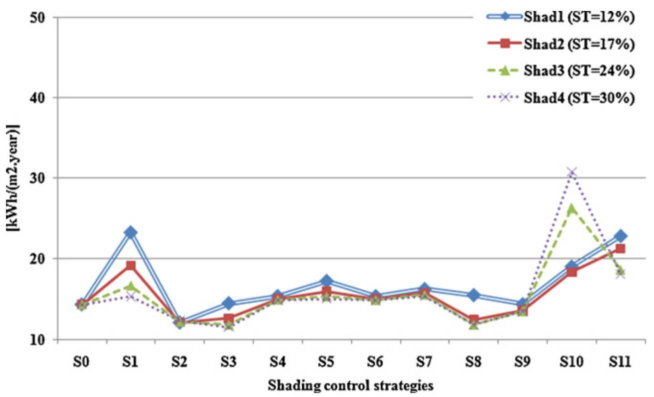

Fig. 11. Overall energy consumption for the four shading transmittance alternatives in each of the control strategies alternatives.

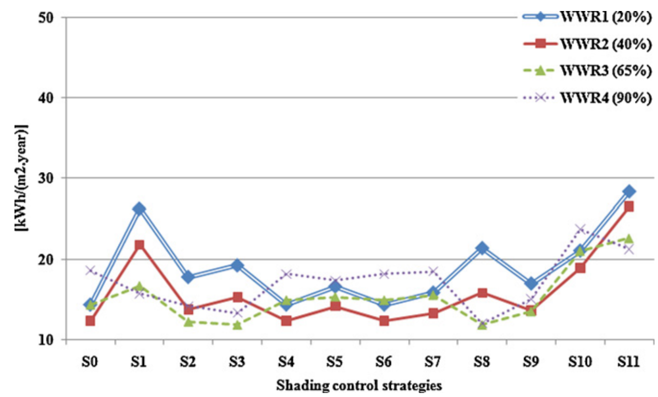

Fig. 12. Overall energy consumption for the four window to wall ratio alternatives in each of the control strategies.

percentage of exact matches between the average ranking of the design alternative and the ranking according to each individual control strategy.

The results of Table 11 reveal that doing the building simulation with the control strategy S5 always leads to the choice of the design alternative that is also the best according to the average of all control strategies (100% match). As far as the ranking of all design alternatives is concerned (and not just the best), strategy S5 is also the one that better replicates the results obtained from the average of all control strategies, with a correspondence of 83%. Fig. 13 illustrates in a graphical form the correlation between the rankings produced by strategies S5 and S11 and the average ranking from all control strategies. It again reinforces the conclusion that strategy S5 is the strategy that better mimics the choice of the average.

In summary, this section provides an analysis of the overall energy consumption resulting from the use of twelve shading control strategies from the point of view of transparent façade design choice. The design alternatives that would lead to the lowest energy consumption were identified, for each scenario, considering the average of the control strategies and the ranking dispersion associated to each strategy. Strategy S5 was shown as being capable of identifying design options that match the ranking for all control strategies in 83% of the cases.

Table 10
Indicators for each design alternative in the range of control strategies S2 to S11. Shadowed boxes show the alternatives with lower (best) average ranking.

	Cooling dominated scenario			Heating dominated scenario			Balanced heating and cooling scenario		
	Best alternative (%)	Average ranking	Ranking ratio (max/min)	Best alternative (%)	Average ranking	Ranking ratio (max/min)	Best alternative (%)	Average ranking	Ranking ratio (max/min)
G1 (ST = 3%)	0	2.8	2.0	10	3.7	4.0	0	3.8	1.3
G2 (ST = 15%)	80	1.3	3.0	0	3.0	2.0	40	1.8	3.0
G3 (ST = 41%)	10	2.3	3.0	0	2.2	1.5	40	1.7	3.0
G4 (ST = 64%)	10	3.6	4.0	90	1.1	2.0	20	2.7	4.0
Shad1 (ST = 12%)	10	3.0	4.0	0	3.8	2.0	10	3.5	4.0
Shad2 (ST = 17%)	60	1.6	3.0	10	2.8	3.0	10	2.7	3.0
Shad3 (ST = 24%)	20	2.1	3.0	0	2.1	1.5	0	2.2	1.5
Shad4 (ST = 30%)	10	3.3	4.0	90	1.3	4.0	80	1.6	4.0
WWR1 (20%)	30	2.1	4.0	0	4.0	1.0	0	3.3	2.0
WWR2 (40%)	60	1.5	3.0	0	3.0	1.0	50	1.8	3.0
WWR3 (65%)	0	2.8	1.5	0	2.0	1.0	40	1.8	3.0
WWR4 (90%)	10	3.6	4.0	100	1.0	1.0	10	3.5	4.0

Table 11
Comparison of the best alternative for each control strategy with the average best alternative.

Design alternatives	Opaque envelope scenarios	Best alternative	Best alternatives for each control strategy									
			S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Glazing types	Cooling dominated	G2	G2	G2	G2	G2	G2	G2	G3	G2	G2	G4
	Heating dominated	G4	G4	G4	G4	G4	G4	G4	G4	G4	G1	G4
	Balanced cooling and heating	G3	G3	G3	G2	G3	G2	G2	G3	G4	G2	G4
Shading devices	Cooling dominated	Shad2	Shad2	Shad4	Shad3	Shad2	Shad3	Shad3	Shad3	Shad1	Shad1	Shad3
	Heating dominated	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad2	Shad4
	Balanced cooling and heating	Shad4	Shad1	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad4	Shad2	Shad4
WWR	Cooling dominated	WWR2	WWR2	WWR2	WWR1	WWR2	WWR1	WWR1	WWR2	WWR2	WWR2	WWR4
	Heating dominated	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4	WWR4
	Balanced cooling and heating	WWR2	WWR3	WWR3	WWR2	WWR2	WWR2	WWR2	WWR3	WWR3	WWR2	WWR4
Percentage of matches with the best alternative			78%	78%	67%	100%	67%	67%	67%	56%	44%	44%
Percentage of matches of the average ranking with the design alternative ranking			61%	69%	67%	83%	67%	78%	44%	69%	47%	56%

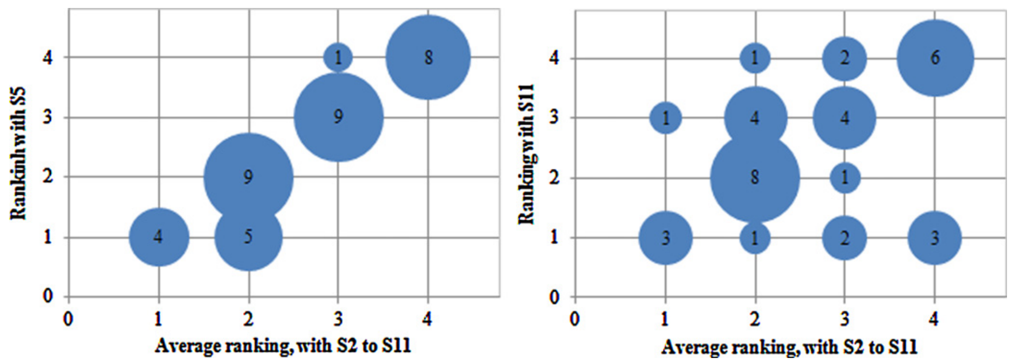

Fig. 13. Rankings with control strategies S2 and S11 vs. the average ranking (number of points overlapped indicated inside the circles).

7. Conclusions

This work started with a review establishing the human requirements for visual comfort in office buildings and the conditions that prompt building occupants to interact with the shading devices and with the electric lights. Numerous publications were found addressing the preferences of workers regarding lighting conditions in offices. There is a large range of reported parameters and even divergent recommendations among the different sources, though all claim to represent occupants preferences in an office building. Workplane illuminance is the most cited and studied parameter. Some other parameters referred to are surface) luminance (of windows, walls and ceiling), solar radiation entering the space and daylight discomfort indexes. However, these are not consistently presented in the literature, so further developments are necessary to reliably characterize occupants comfort preferences and response to lighting conditions in order to allow for robust comparisons. Regarding manual operation of window movable shadings or the change of the artificial lighting state, a significant number of occupant behavioral patterns and models were found too, with significant discrepancies among the bibliographic sources, especially in terms of shading devices control.

The simulation case study carried out to understand the impact of the use of different control patterns and behavioral models on the selection of transparent façade design options revealed that these directly influence the selection of design alternatives. The results showed that different behavioral models, even if all documented in the scientific literature, result in different choices of “best design alternative”. This was remarkable on the office with balanced heating and cooling loads, and to some extent in the cooling-dominated and in the heating-dominated scenarios. Furthermore, the results show that even when not changing the merit order of design alternatives, the consideration of different control patterns and behavioral models has a significant impact on the computed energy performance.

Since different behavioral models lead to different choices of best design alternatives but there is no clear indication of which behavioral models are best, the option of choosing a design alternative based on average ranking computed with the results of all behavioral models was considered. The results show that the control strategy S5 (shading is active if DGI is higher than 20) is the one that, considered alone, replicates most reliably the choices made with the average ranking. Regarding the choice of the best design alternative, choosing with S5 alone always led to the same choice as choosing with the average. This result shall not be interpreted as proving that the behavioral model S5 is more realistic or valid than the others: it just means that it better represents the average of the whole group of models considered in terms of the results that they produce. Therefore, this study reinforces the need of further research focused on the identification of behavioral models with high statistical significance, developed from campaigns of post-occupancy monitoring of a large number of office buildings.

Acknowledgments

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