# Energy and luminous performance simulation for venetian blinds control strategies

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## Abstract

Considering the benefits of daylight to humans and the inefficiency of manual blind operation by the users, automated blind control strategies represent an opportunity for daylighting improvement with both user visual comfort and building energy efficiency impacts.

In this work, several strategies for venetian blind control are proposed and simulated with building energy simulation software, using a DECivil IST office room as a case study. The strategies are simulated for different conditions, such as: façade orientation (South, East, West and North); blind position in relation to the window (interior or exterior); period of the year (summer or winter); type of blind (simple venetian blinds or split blinds); and different climatic conditions (four European countries).

In order to quantify the performance of the control strategies performance indexes were created. The visual comfort performance index was calculated recurring to six different visual comfort metrics. The energy consumption performance index was calculated recurring to the final energy needs of the HVAC equipment and the electric lighting. Lastly the global performance index was calculated with the two other calculated indexes

A comparison of energy and visual comfort performance among strategies is made. As a final result, best suited strategies are recommended according to the conditions which the office is exposed to.

**Keywords:** Blind Automation, Blind Control Strategy, Energy Efficiency, Visual Comfort, Building Simulation, Daylighting

## 1. Introduction

Energy efficiency is of great importance in an environmental context as being one of the most relevant possible areas of intervention to reduce energy consumption and greenhouse gas emissions. Furthermore there has been an increase in energy demand worldwide while some estimations point to 1,2 billion people (17% of world population) with no access to electricity (OECD & IEA, 2015) and according to OECD energy demand will grow 50% to 200% until 2050 (World Energy Council, 2013).

Good lighting and in particular good daylighting provides several health benefits. Some studies show that sunlight exposure improves wellbeing sensation and reduces drowsiness (Aries, 2005; Kaida et al., 2006; Kosuke et al., 2006; van Bommel, 2006), although the same effect has been observed with artificial lighting (Aries, 2005; Smolders et al., 2012).

One study found a positive correlation between increased daylight and higher academic performance in various schools (Heschong Mahone Group, 1999a) and another study found a positive correlation between increased solar lighting and more sales at various stores (Heschong Mahone Group, 1999b).

In favour of the study of control strategies benefits of daylight, there is the possibility of inefficient manual blind control. Manual blind operation by users tends to be done once a day and the blinds stay in the resulting position through the day (Galasiu & Veitch, 2006; Rubin et al., 1978; Ruck et al., 2001; Zhang & Barrett, 2012).

In Vine et al. (1998) it was concluded that automated blind control is less accepted by the users than manual blind control, in spite of manual blind control being reported as more related with visual discomfort by natural or artificial glare sources than automated blind control situations.

## 1.1. Visual comfort metrics

Visual comfort is important in any daylighting system. Various metrics were used in this work to measure different aspects of visual comfort. Because the lack of space in this extended abstract, only some metrics are presented here, which are organized in three types: amount of light; uniformity of light; and glare.

### 1.1.1. Amount of light metric

The metric *Useful Daylight Illuminance* (UDI) represents a fraction of time in a year when the values illuminance on the work plane are between two values. Besides the superior and inferior limits of this metric, there is usually the autonomy value. Illuminances below this threshold are considered useful but need to be complemented with electric light, illuminances above this value are considered useful but do not need to be complemented with additional light.

Defined by Mardaljevic & Nabil (2005) this metric is typically presented in percentage and calculated between 100 lux and 2000 lux, although it can also be calculated with different values (see Table 1).

**Table 1 – UDI reference values**

| References | Inferior limit (lux) | Autonomy value (lux) | Superior limit (lux) |
|---|---|---|---|
| Bellia et al. (2015); Chaiwiwatworakul & Chirarattananon (2013); Gilani et al. (2015); Hu & Olbina (2011); Manzan (2014); Mardaljevic (2006); Mardaljevic & Nabil (2005); Nabil & Mardaljevic (2006); Olbina & Hu (2012); Ramos & Ghisi (2010); Reinhart et al. (2006); Reinhart & Weissman (2012); Shen & Tzempelikos (2013); Tzempelikos & Shen (2013); Zelenay (2011) | 100 | 500 | 2000 |
| Mardaljevic et al. (2012) | 100 | 300 | 3000 |
| Hachem et al. (2014) | 300 | 500 | 2500 |
| David et al. (2011) | 300 | 300 | 8000 |

### 1.1.2. Light uniformity metrics

A good light distribution results in less contrast between different lighting levels which contributes for less stain on the eyes and helps in the visual adaptation to different areas. This type of metric is generally measured with illuminance levels on the work surface.

Visual discomfort occurs when there is an excess of light but can also occur if a given surface has pronounced contrast between illuminance values. The uniformity of illuminance is calculated on a surface for a given moment and can take form with the calculation of two different ratios. The uniformity ratios are calculated by the ratio between the minimum illuminance of that surface and depending on the ratio either to maximum surface illuminance ($U_{max}$) of the surface's average illuminance ($U_{avg}$). On Table 2 you can see the reference values of the different ratios.

**Table 2 – Reference values for illuminance uniformity metrics ($U_{max}$ and $U_{avg}$)**

| References | $U_{max}$, acceptable | $U_{max}$, recommended | $U_{avg}$ |
|---|---|---|---|
| Dubois (2001a) (2001b); Saunders (1969); Slater & Boyce (1990) | >0,5 | >0,7 | - |
| CIBSE (2012) | >0,2 | - | >0,7 |
| Technical Committee CEN/TC 169 (2002) | >0,7 | - | - |
| Dubois (2001b) | - | - | >0,8 |

### 1.1.3. Glare metric

Glare metrics have the goal of identifying glare situations for users. These metrics, in general, are based on a surface's or a light source's luminance level. Here is described tone of these metrics, the *Daylight Glare Index* (DGI).

DGI, sometimes also called *Discomfort Glare Index* (Yao, 2014), was created with the purpose to predict and quantify glare sensation of large glare sources like windows. This glare index is the most used for natural light (Osterhaus, 2005; Yao, 2014) and can be calculated with the equation proposed by Chauvel et al. (1982).

This index has some limitations. Because it only considers the average window luminance, it does not take into account direct light. This is not very realistic as direct lighting plays a big role in visual discomfort and can cause more glare than its corresponding average window luminance. Furthermore DGI values are not very reliable when the light source occupies a big portion of the field of view or when the wall luminance is similar to window luminance (Bellia et al., 2008). Additionally, there are some differences between predictions of DGI values and real sky conditions (Bellia et al., 2008).

The most used DGI reference value is 22 (Chaiwiwatworakul et al., 2009; Chauvel et al., 1982; Oh et al., 2012; Yao, 2014), although some other values may be found. Furthermore this value is also used in automated blind control strategies (see 1.2).

## 1.2. Blind Strategies

Consulting other papers several possible automated blind strategies were identified and separated on categories, depending on the parameters used for the control: radiation; glare index; illuminance; block direct radiation. On Table 3 are the identified strategies separated by categories.

**Table 3 – Automated blind strategies used by other authors**

| Category | Reference | Description |
|---|---|---|
| **Radiation** | da Silva et al. (2012) | Close the blinds if transmitted vertical solar radiation + diffuse solar radiation is greater than 100 W/m$^2$ and open otherwise. |
| | da Silva et al. (2012) | Close the blinds if transmitted vertical solar radiation + diffuse solar radiation is greater than 200 W/m$^2$ and open otherwise. |
| | EN ISO 13790 (2006) | Close the blinds if irradiance is bigger than a 300 W/m$^2$ and open otherwise. |
| | Guillemin & Morel (2001) | Close the blinds if direct solar radiation is greater than 100 W/m$^2$ and close otherwise. |
| | Moeseke et al. (2007) | Close the blinds if irradiance is bigger than a value between 200-300 W/m$^2$ and open otherwise. |
| | Newsham (1994) | Close the blinds if the solar beam intensity is greater than 233 W/m$^2$ and close otherwise. |
| **Radiation / glare index** | Lee & Selkowitz (1994) | Close blinds if direct transmitted solar radiation is greater than 94,5 W/m$^2$ or if GI exceeds 20 and close otherwise. |
| | Aste et al. (2012) | Close blinds if irradiance on window is greater than a 200 W/m$^2$ (summer only) or if GI exceeds 19 and close otherwise. |

| | | |
|---|---|---|
| **Glare index** | da Silva et al. (2012) | Close the blinds if DGI is greater than 20 and close otherwise. |
| | da Silva et al. (2012) | Close the blinds if DGI is greater than 24 and close otherwise. |
| | Oh et al. (2012) | Close the blinds if DGI is greater than 22 and close otherwise. |
| | Oh et al. (2013) | Adjust slat angle to reduce energy consumption while maintaining DGI below 22. |
| **Glare index/ illuminance** | Chaiwiwatworakul et al. (2009) | Adjust slat angle to maintain DGI below 22 and if possible maintain work plane illuminance above 500 lux. |
| **Illuminance** | Ruck et al. (2001) | Adjust slat angle to maintain work plane illuminance on 500 lux. |
| | Olbina & Hu (2012) | Adjust slat angle to allow the highest illuminance possible below 2000 lux. |
| **Block direct radiation / illuminance** | Lee et al. (2009) | If vertical exterior illuminance is greater than 30 klux adjust slat angle to cut-off and if necessary close further to maintain work plane illuminance on 570-670 lux and if vertical exterior illuminance is lesser than 30 klux adjust slat angle to maintain work plane illuminance on 570-670 lux. |
| | Vine et al. (1998) | Adjust blind height or slat angle to block direct solar radiation and if necessary close further until illuminance is 793 lux in the morning and 696 lux on the afternoon. |
| | DiBartolomeo et al. (1996) | Adjust slat to cut-off angle and if necessary close the slats until illuminance is 485-675 lux. |
| | Lee & Selkowitz (1994) | Adjust slat to cut-off angle and if necessary close the slats until illuminance is below 538 lux. |
| **Block direct radiation** | Chaiwiwatworakul et al. (2009) | Adjust slat to cut-off angle. |
| | Chaiwiwatworakul et al. (2009) | Adjust slat to cut-off angle and when the sky is cloudy open slats. |
| | Vartiainen (2001) | Adjust slat to cut-off angle. |
| | Athienitis & Tzempelikos (2002) | Adjust slat angle to cut-off angle maintaining the height of the blinds to allow an outside view. |

# 2. Strategies Simulating

## 2.1. Control Strategies

14 blind control strategies were simulated (see Table 4 and Figure 1) in this work, where 11 consider simple venetian blinds, and three consider the use of split blinds. The difference between the split blind strategies is that the top segment has the slats completely opened (horizontal).

The considered strategies were organized in three groups: static strategies; regulation strategies; and dynamic strategies. The static strategies represent base control cases, which provide simulation results for comparison purposes. The regulation strategies represent methods of calculating the impact of shading devices according to the Portuguese regulation and EN ISO 13790 (Despacho n.º 15793-K/2013, 2013; EN ISO 13790, 2006; Portaria n.º 349-D/2013, 2013).

**Table 4 – Control strategies**

| Strategy | Type of strategy | Type of Blind | Description |
|---|---|---|---|
| **E1** | Static | Simple | Fully opened blinds |
| **E2** | | | Fully closed blinds |
| **E3** | | | Slats at 90º (open) |
| **E4** | | | Slats at 45º |
| **E5** | Regulation | | Blinds closed 60% of daytime |
| **E6** | | | Blinds closed covering 60% of window area |
| **E7** | | | Blinds close if solar radiation is greater than 300 W/m$^2$ |
| **E8** | Dynamic | | Slats with cut-off angle |
| **E9** | | | Blinds close if DGI is greater than 22 |
| **E10** | | | Slats as open as possible while DGI is maintained below 22 |
| **E11** | | | Slats as closed as possible while work plane illuminance above 500 lux |
| **E12** | Static | Split blind | Top segment with 90º slat angle and lower segment with closed slats |
| **E13** | Dynamic | | Top segment with 90º slat angle and lower segment with slats at cut-off angle |
| **E14** | | | Top segment with 90º slat angle and lower segment with close the blinds if DGI is greater than 22 |

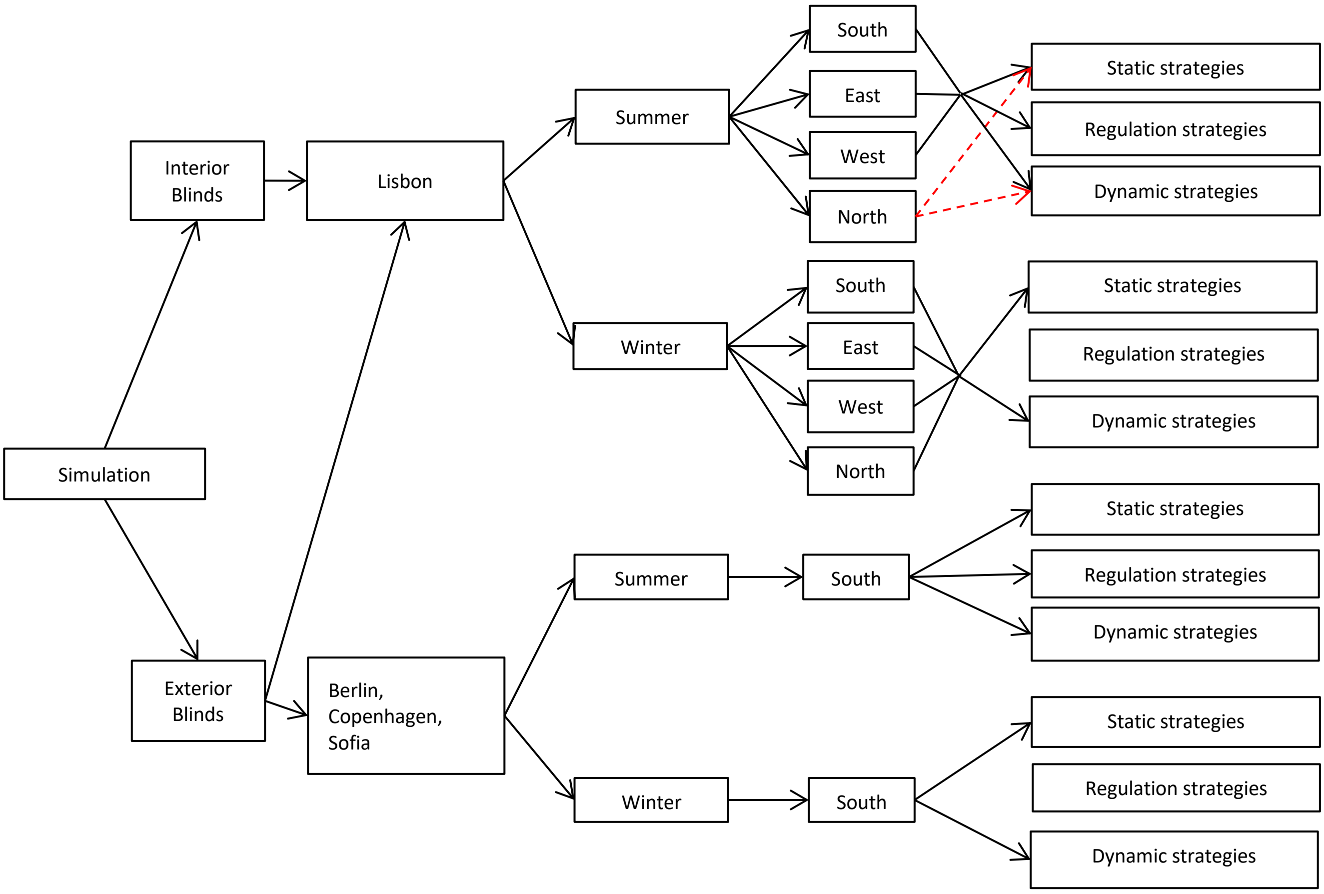


**Figure 1 – Diagram with the performed simulations**

## 2.2. Performance metrics

Besides visual comfort, also energy consumption was simulated. To evaluate the performance of the impact on visual comfort three aspects were measured: quantity of light, uniformity of light; and glare. To measure the quantity of light the metric used was the percentage of time the UDI was within the accepted values (500 lux to 2000 lux). To quantify the uniformity of light, the three metrics presented above were calculated, the percentage of time the ratios where above the three values on Table 5. To measure glare the metric used was the percentage of time DGI was below 22.

To measure energy performance the final energy needs of the HVAC system and the electric light were measured and added.

To compare the performances of the strategies a multi criteria analysis method was used, proposed by Díaz-Balteiro & Romero (2004). Aggregated performance indexes were created for energy consumption, visual comfort and also a global performance index. This was done attributing weights to each of the metrics mentioned above. Figure 2 shows the weights used to calculate the global performance.

**Table 5 – Reference values used for uniformity of light ratios**

| **Ratios** CIBSE (2012); Dubois (2001a) (2001b); Saunders (1969); Slater & Boyce (1990) | **Acceptable** | **Minimum** |
|---|---|---|
| $U_{min}/U_{max}$ | 0,7 | 0,5 |
| $U_{min}/U_{avg}$ | - | 0,7 |

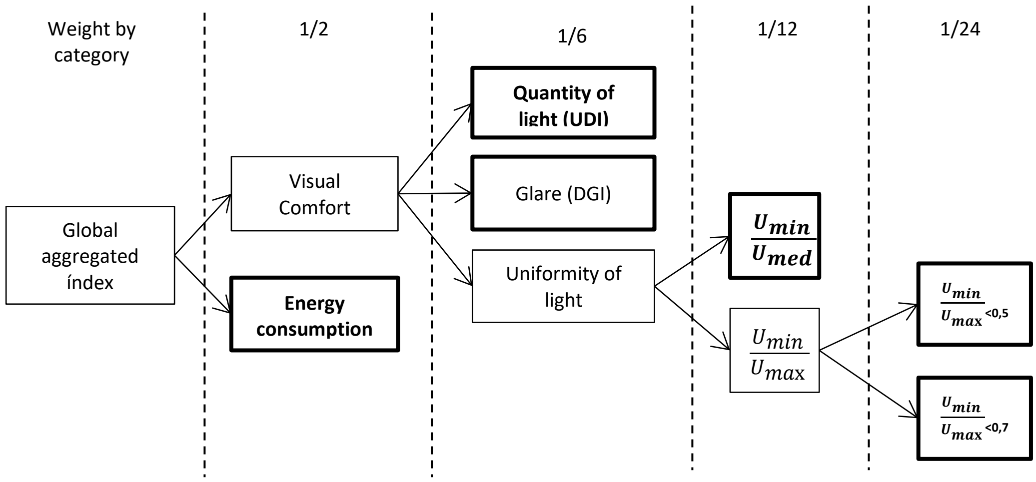


**Figure 2 – Weight distribution on global performance index**

## 2.3. Model

The office modelled for the simulation is a real single occupancy office in the second floor of the civil engineering building in IST, Lisbon. It has only one exterior surface and it has a window with split blinds. The floor area is 14.06 $m^2$ and its height is 3.15 m.

The software used to simulate the model was version 8.1.0 of *Energy Plus*. EMS (*Energy Management system*) control method was used to perform some tasks like calculating metrics and executing some strategies. Adding to that on some strategies there was the need to perform co-simulations between EP and Matlab, this was done using the toolbox MLE+.

It was considered in EP that the HVAC system maintained a temperature above 20ºC during the winter and below 25ºC during the summer (Portaria n.º 349-D/2013, 2013). For internal gains it was considered the constant value of 7 W/$m^2$ (Ministério das Obras Públicas Transportes e Comunicações, 2006). The air renovation rate was set to 1 rph in the winter and 1,5 rph in the summer above the minimum specified in the regulations (Portaria n.º 349-B/2013, 2013). The seasons considered for the simulations were the astronomical summer (June 21st to September 21st) and the astronomical winter (December 21st to March 21st). The work plane was set at 80 cm of height with a surface of 90 cm by 70 cm, 12 cm from the exterior wall, as seen in Figure 3.

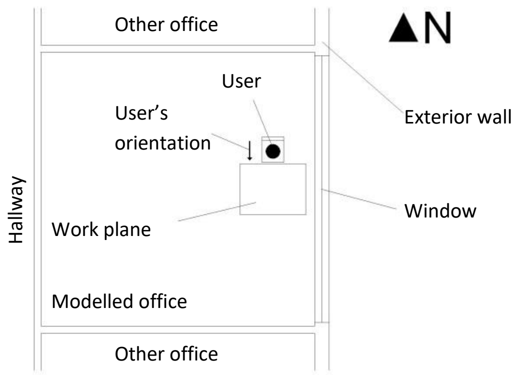


**Figure 3 – Modelled office map, location of use rand work plane**

# 3. Results and discussion

Even though all the simulations mentioned in 2.1 were developed (Leal, 2016), only some results will be presented here due to space limitations. Namely, the results for interior and exterior blinds as well as the results for European countries will be presented.

## 3.1. Impact of Blind position

For both winter and summer the lighting conditions were the similar for the same strategy with exterior and interior blinds and the same applied for electric light consumption.

The difference between exterior and interior blinds was on the HVAC energy consumption, cooling need and heating needs. In the summer for all orientations the exterior blinds were less energy demanding than the interior blinds. In the winter the opposite was true and the interior blinds were the less energy demanding for all orientations.

Although each season had a different better solution it was concluded taking into account both seasons the exterior blinds were the less energy demanding option for the two seasons combined, on an annual analysis. As seen on Table 6 the average HVAC energy needs added for summer and winter is significantly lower for exterior blinds.

**Table 6 – Average consumption (HVAC only) per strategy (all strategies considered)**

| | Average final energy needs (kWh/m$^2$) | |
|---|---|---|
| | **Interior blinds** | **Exterior blinds** |
| **Summer** | 15,40 | 10,45 |
| **Winter** | 1,75 | 2,46 |
| **Total (summer + winter)** | 17,15 | 12,91 |

## 3.2. Simulations in other European countries

To better understand the impact geographic location would have on the better performant strategies simulation were performed for Berlin in Germany, Copenhagen in Denmark and Sofia in Bulgaria. These locations are in higher latitude, which means the light exposure time as well as sun height is different. Furthermore in these locations the temperature is in general lower, that leads to the heating needs having more impact than in Lisbon.

In the summer for all the other European locations E4 (slat angle at 45º) was the best performant strategy, E11 (slats illuminance) was a close second and in Copenhagen E3 (slat angle at 90º) also had a very good global performance. In Figure 4 are represented the performance indexes for visual comfort, energy consumption and global for each strategy for all locations. These results differ from Lisbon's where, for the same orientation, the best performant strategy was E11. In spite of that the two best performant strategies were the same in all locations, E11 and E4.

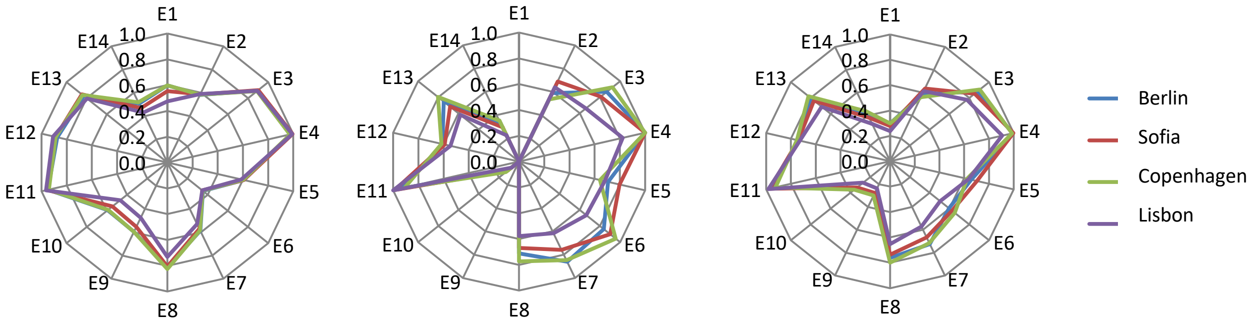


**Figure 4 – Aggregated performance index for visual comfort (left), energy consumption (centre), global performance (right) for summer and the south orientation**

In the winter for all the other European locations strategies E1 (fully open), E9 and E10 were the best performant with the same global performance. In Figure 5 are represented the performance indexes for visual comfort, energy consumption and global for each strategy for all locations. It was concluded that the best strategy would be to leave the blinds always open. These results differ from Lisbon's where, for the same orientation, the best performant strategies were E11 and E13 (split blinds cut-off) followed by some distance by E8 (cut-off), E1, E9 (DGI) e E10 (slats DGI).

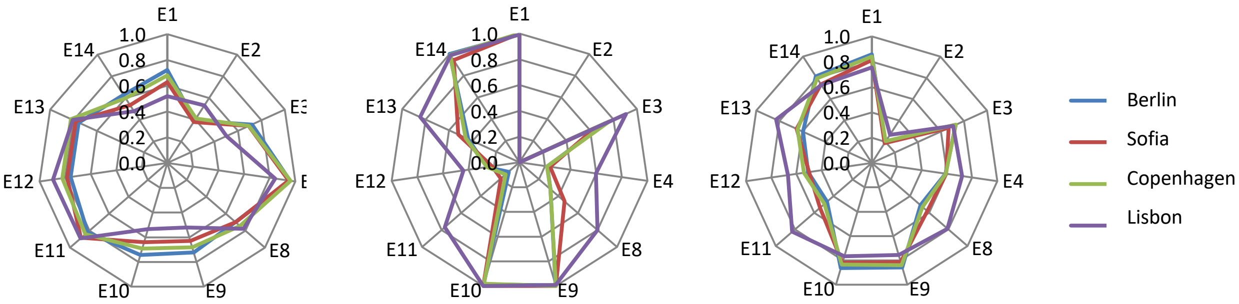


**Figure 5 – Aggregated performance index for visual comfort (left), energy consumption (centre), global performance (right) for winter and the south orientation**

# 4. Conclusion

When comparing the performance between interior blinds with exterior blinds it was found that the visual comfort performance was similar, but in the summer the external blinds had better thermal performance while in winter the interior blinds had better thermal performance. Calculating average total consumption (summer + winter) for Interior and exterior blinds it was concluded that the external blinds were the better solution (more performant) to use during the whole year in Lisbon.

Amongst the fixed strategies (E1 (fully open), E2 (fully closed), E3 (slat angle at 90º), E4 (slat angle at 45º) and E12 (split blinds closed)), E4 was the better performant in the summer for any façade orientation. IN the winter the same applied to E3, except for the south orientation where none of the fixed strategies has a good performance. Adding to that E1 was the worst performant strategy in the summer whilst in the winter was the E2 strategy, for any orientation.

The regulatory strategies (E5 (60% of day time), E6 (60% window area) and E7 (300 $W/m^2$)), did not provide similar results for visual comfort performance for any orientation. Furthermore those strategies did not have similar results for energy consumption performance; this means there are several methods to calculate the energy consumption impact of window blinds that can present in different results. These type of strategies did not have good global performance amongst other strategies, except for E5 which was the fourth most performant with the east orientation.

Strategies which used the DGI (E9 (DGI), E10 (slats DGI) and E14 (split blinds DGI)) as a control parameter were worst performants for the illuminance uniformity metrics when compared to the dynamic strategies, this was more noticeable in summer simulations rather than in winter simulations.

Amongst dynamic strategies (E8 (cut-off), E9, E10, E11 (slats illuminance), E11 was the best performant for any orientation and in both summer and winter, in many instances had the best visual comfort performance and sometimes also had the best energy consumption performance. Only during the winter other strategies came close the E11's performance. For the south orientation E11 and E13 (split blinds cut-off) had the same global performance and for the north orientation E10 had a performance close to that of E11's.

For the east orientation both in summer and winter E9 was the least performant strategy, while for the North orientation E8 was the least performant in both seasons. For the south orientation, in the summer, the least performant strategy was E9 with the same global performance index than E1 and for the winter the least performant was E12. For the west orientation, in the summer, the least performant strategy was also E9 while for the winter the least performant was E14.

Amongst all the simulated strategies the most performant was a dynamic strategy, E11. The least performant strategy was E1 for summer simulations and E2 for winter simulations.

When comparing the strategies with the slip blinds (E12, E13 and E14) with its equivalent simple venetian blind strategies (E2, E8 and E9 respectively), it was concluded that in general the split blind strategies were globally better performant, these strategies also had better visual comfort performance whilst only sometimes had also better energy consumption performance.

For a broader scope some simulations were performed for other European cities; Belin in Germany, Copenhagen in Denmark and Sofia in Bulgaria. These simulations were only executed for the south orientation and their conclusions are presented below.

Amongst the strategies with the slip blinds (E12, E13 and E14) with its equivalent simple venetian blind strategies (E2, E8 and E9 respectively), it was concluded that that in general the split blind strategies were globally better performant, except for E14. E12 and E13 had the best visual comfort performance as well as the best energy consumption performance, with the exception of the summer simulation for Sofia, Bulgaria where the same analysis applies but for strategies E13 and E14. These results match the ones from Lisbon simulations where split blinds where in general better performants than simple venetian blinds.

For the summer in general E4 strategy was the best performant amongst all the simulated strategies followed closely by E11. For the winter keeping the blinds always open was the best strategy, the best performant strategies were: E1; E9; E10. E11 was the second most performant in this scenario. It should be noticed that for any season the best performant strategies were static strategies. This differs from Lisbon's results where a dynamic strategy was the best performant (E11) for both winter and summer.

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