# Numerical simulation of the performance of glazing systems with solar control films

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**Abstract**

Buildings with large window areas tend to have more heat gains/losses through the glazing systems, which increase the cooling and heating loads. Applying solar control films (SCFs) on glazing systems can reduce the heat gain, annual energy consumption and peak demand load. The main objective of the present study is to evaluate the thermal, optical and energy performance of different types of SCFs applied on glazing systems. Three adjacent office rooms located in the first floor of the Mecânica III building of Instituto Superior Técnico, in Lisbon, were used as case study. A building energy simulation model of the offices was built in EnergyPlus, calibrated by experimental results, and then used to simulate the performance of the glazing systems. From the considered SCFs, RHE20SIERHPR has the highest thermal and optical performance due to its low visible transmittance ($\tau_v$=16%) and solar heat gain coefficient ($g$=0.2), allowing to achieve temperature and glare comfort during 41% and 43% of working hours. The film PR70EXT ($\tau_v$=70%; $g$=0.48) has the highest energy performance, enabling to achieve the highest annual reduction (38%) of the electricity consumption, electric peak demand load and $CO_2$ emissions. Considering different solar orientations, the highest energy performance was obtained when installing PR70EXT on a West oriented window. In a multi-criteria evaluation approach, RHE20SIERHPR or PR70EXT were selected as the best alternatives when assigning preferred importance to thermal and visual comfort or energy saving and $CO_2$ emission reduction criteria, respectively.

**Keywords:** Solar control film, Numerical simulation, Thermal performance, Optical performance, Energy consumption

## 1. Introduction

The rapid rise of the world's population and its lifestyle quality has led to a global increase in energy needs. Today's energy systems are dominated by fossil fuels, which are responsible for the emission of greenhouse gases, primarily $CO_2$, and act as drivers of global climate change. Therefore, a transition to a more efficient use of energy is needed.

Globally, in 2015, the building sector was responsible for 30% of the final energy and over 50% of the electricity consumptions [1]. While new buildings are usually more efficient because they are designed with more demanding regulation, the existent ones tend to have poorer energy efficiency. Although large glazed areas can provide luminous quality, they facilitate heat transfer between the interior and exterior, increasing the cooling and heating loads. Applying solar control films (SCFs) on glazing systems can originate health, environmental and economic benefits, by reducing the transmission of ultraviolet radiation ($\tau_{UV}$), solar heat gain coefficient (SHGC), annual energy consumption and peak demand load [2-7]. On the other hand, these films also reduce the visible transmittance of the glazings, which may lead to an increase of the lighting energy consumption to provide visual comfort [2, 3].

Even though studies investigating the effect of SCFs on buildings' performance are relatively scarce, they conclude that the application of SCFs on buildings' glazings can result in energy savings and promote a more comfortable indoor environment. The key conclusions of some of these studies, experimental and numerical, are described below. In an experimental study, conducted by Li *et al.* [2], diffuse and direct solar radiation were reduced by 30% and 50%, respectively, in the presence of a SCF applied in an office, in China. In an experimental study conducted on an office with a SCF, located in China, Li *et al.* [3] obtained a reduction of 40% of indoor daylight illuminance levels, electric lighting daily use savings varying from 16.8% to 28.9% and a reduction of the cooling energy needs up to 62 kWh/day. Considering the application of SCFs on different building types, Li *et al.* [4] obtained the largest energy savings for office applications through numerical simulation, varying between 77 and 90 kWh/year per unit area of SCF. A decrease up to 8% of the electricity consumption in a commercial building with large glazed areas, during the cooling season, was obtained in a numerical study conducted by Yin *et al.* [5]. When assessing the impact of exterior SCFs, Bahadori-Jahromi *et al.* [6] obtained for an hotel building in the United Kingdom an annual heating energy consumption increase of 2% and an annual global energy saving of about 2%, which mainly resulted from a reduction, up to 35%, of the annual cooling energy consumption. In a numerical study conducted on office rooms in Lisbon, Portugal, by Pereira *et al.* [7], the cooling energy needs were reduced up to 73% and 93%, and the primary energy consumption for climatization was reduced up to 46% and 59%, when considering, respectively, interior and exterior SCFs applied on glazings.

The main aim of this study is to evaluate the thermal, optical and energy performance of different types of SCFs applied on the glazing systems of office rooms, in Lisbon, in order to understand their influence on the energy consumption and on the indoor thermal and visual comfort conditions. A numerical simulation was developed using EnergyPlus and then calibrated with experimental data. The results were used in a multicriteria analysis to help selecting the SCF with the best global performance.

## 2. Case Study and Experimental Campaign

Three adjacent office rooms located in the first floor of Mecânica III building (Fig. 1) of Instituto Superior Técnico (IST), in Lisbon, were used as case study. The building, built in 2000, has two upper floors consisting mainly in individual office rooms and two underground floors consisting mainly in laboratories. The location of the offices used as case study in the building is shown in Fig. 2, in red. The three offices are located on the top floor of the building and have the same height (2.97m), solar orientation (Southeast), occupation (1 person) and similar floor area (19m$^2$). The offices' envelope opaque elements were considered adiabatic, except the exterior wall (U=2.63W/m$^2$K) and the flat roof (U=0.77W/m$^2$K). The offices' original glazing system, with a glazing area of 10.38 m$^2$, consisted on a conventional double clear float glazing with a gap air (6+12A+4mm) and a green aluminium frame without thermal cutting. An interior SCF (R35SISRHPR) was installed on the original glazing system, in 2006, in order to reduce thermal and visual discomfort. Manual venetian blinds with metallic horizontal slats provide shade to the glazing systems. Because of the building's geometry, the offices' exterior façade oriented Southeast suffers a shading effect caused by the protruding south façade, as shown in Fig. 2 (dotted orange line). This shading effect is normally noticeable around 12h, affecting first the office 4.7 and then gradually the others. The location of the offices' glazing systems on the exterior façade is identified in Fig. 3. In each office two ceiling incandescent luminaires (200W each), a desk luminaire, a desktop computer and a laptop computer are present. Thanks to a Variable Refrigerant Volume (VRV) unit with a seasonal energy efficiency ratio (SEER) of 7.98 and a seasonal coefficient of performance (SCOP) of 4.43, occupants can control the temperature of their office during working hours with an established setpoint of 22±2°C.

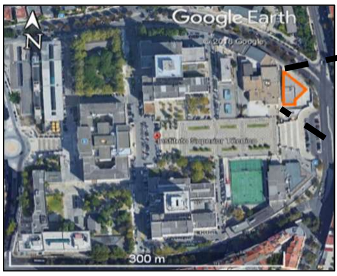


Fig. 1 – Location (orange) of the Mecânica III building in IST (Google Earth 2018).

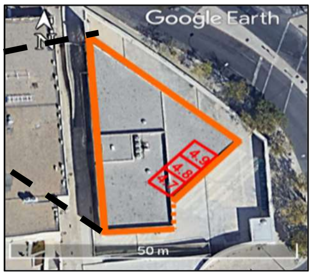


Fig. 2 – Location (red) of the offices in the Mecânica III building (Google Earth 2018).


Fig. 3 – Identification of the offices' glazing systems on the exterior façade.

An experimental campaign with the purpose of evaluating the thermal and optical performance of glazing systems with and without SCFs was carried out in the abovementioned offices by Lourenço [8], using the measuring equipment shown in Fig. 4. This campaign was conducted simultaneously in all the offices during two periods: from 11st March to 16th April (heating season period) and from 28th May to 28th June (cooling season period). An exterior SCF (RHE20SIERHPR) was installed on the glazing system of office 4.7, the original interior SCF (R35SISRHPR) was maintained on the glazing system of office 4.8 and the film was removed from the glazing system of office 4.9. Office 4.9 (without SCF) is considered the reference office, for comparison purposes. The thermal and optical properties of these three glazing systems are present in Table 1 of chapter 3.

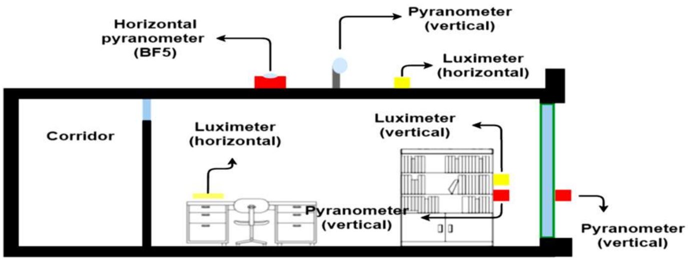


Fig. 4 – Location of the measuring equipment (except thermocouples) used during the experimental campaign [9].

By analysing the collected data, Lourenço [8] has concluded that the glazing system with the exterior SCF (more reflective) had the worst optical performance and the best thermal performance, reducing the incoming visible light and the indoor air temperature because of its lower visible transmittance, SHGC and solar transmittance. Lourenço [8] also concluded that the glazing system with the interior SCF had a similar thermal performance to the reference glazing, having contributed to the absorption of radiation and its back inside reflection, increasing the indoor air temperature. As a result of the different SCFs' performances, a numerical study (chapter 3) was carried out with new SCFs, installed on the exterior or interior surfaces of the reference office's glazing system, to better understand the effect that their properties and installation surface have on their performance.

## 3. Numerical Simulation

The programs and respective outputs used to create the numerical simulation to assess the performance of the glazing systems are shown in the flowchart of Fig. 5. A 3D geometric model of the offices with the shading surfaces (protruding wall and parapet) was generated using SketchUp (Fig. 6). The window software Optics6 and Window7.6 were used to estimate the thermal and optical properties of the glazing systems without and with SCFs (Table 1). The outputs obtained from the abovementioned programs were used as input parameters in the EnergyPlus model. The model was calibrated comparing the simulation results with the experimental data from Lourenço [8]. For the calibration simulation, the weather file (EPW) of Lisbon was edited using the Elements program in order to consider the meteorological data collected during the experimental campaign. After calibrated, the simulation model was used to assess the performance of the glazing systems when associated with the weather file (EPW) of the typical meteorological year climate data of Lisbon. Apart from the original glazing (without SCF), the application of the two films used during the experimental campaign and ten new ones with different properties was simulated with the purpose of allowing a better comparison and evaluation of the performance of glazing systems with SCFs.

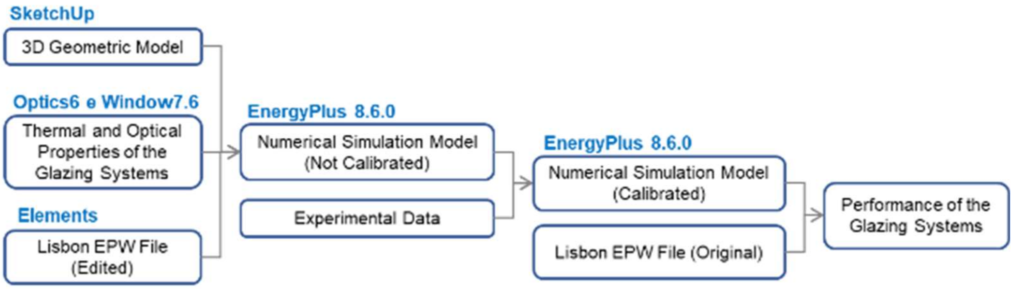


Fig. 5 – Flowchart of the programs used to assess the performance of the glazing systems.

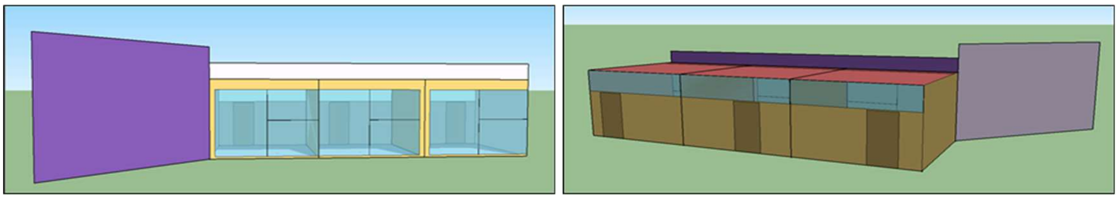

Fig. 6 – SketchUp 3D model of the offices: outdoor view (left) and indoor view (right).

Table 1 – Thermal and optical properties of the glazing systems, ordered by increasing visible transmittance, obtained from Optics6 and Window7.6.

| | | Properties | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCF (Manufacturer) | P[1] | $U$ [W/m²K)] | $g$ [-] | $\tau_{vis}$ [%] | $\rho_{visE}$ [%] | $\rho_{visI}$ [%] | $\tau_{sol}$ [%] | $\rho_{solE}$ [%] | $\rho_{solI}$ [%] | $\alpha_1$ [%] | $\alpha_2$ [%] | $\tau_{UV}$ [%] |
| RHE20SIERHPR* | E | 2.71 | 0.15 | 16 | 62 | 58 | 10 | 63 | 44 | 26 | 1 | < 0.1 |
| R35SISRHPR* | I | 2.63 | 0.40 | 26 | 45 | 46 | 18 | 36 | 50 | 14 | 32 | < 1.0 |
| LEP35 (Llumar) | I | 1.86 | 0.32 | 31 | 43 | 26 | 18 | 38 | 50 | 17 | 28 | < 1.0 |
| RE35SIARXL (3M) | E | 2.71 | 0.30 | 32 | 36 | 37 | 22 | 39 | 31 | 37 | 2 | 0.1 |
| PR40EXT (3M) | E | 2.71 | 0.30 | 38 | 7 | 12 | 20 | 24 | 12 | 54 | 1 | < 0.1 |
| RE35NEARXL (3M) | E | 2.71 | 0.39 | 40 | 12 | 18 | 28 | 13 | 16 | 57 | 2 | 0.1 |
| R50 (Llumar) | I | 2.67 | 0.51 | 43 | 30 | 29 | 30 | 25 | 32 | 15 | 30 | < 1.0 |
| Silver50Xtra (Hanita Coatings) | E | 2.71 | 0.37 | 43 | 29 | 30 | 30 | 31 | 26 | 37 | 2 | < 0.1 |
| Titan50Xtra (Hanita Coatings) | E | 2.71 | 0.41 | 47 | 20 | 23 | 33 | 23 | 21 | 42 | 3 | < 0.1 |
| LEP70 (Llumar) | I | 1.92 | 0.52 | 62 | 14 | 8 | 38 | 20 | 29 | 15 | 28 | < 1.0 |
| PR70EXT (3M) | E | 2.71 | 0.40 | 63 | 11 | 14 | 32 | 26 | 13 | 40 | 2 | < 0.1 |
| PR90EXT (3M) | E | 2.71 | 0.58 | 79 | 15 | 15 | 53 | 30 | 20 | 13 | 4 | < 0.1 |
| Without SCF | | 2.72 | 0.76 | 81 | 15 | 15 | 70 | 13 | 13 | 12 | 6 | 54.0 |

* SCFs present during the experimental campaign
[1] Position: I - Interior; E - Exterior

From the computed results of the thermal and optical properties of the glazing systems presented in Table 1, it can be noticed that the thermal transmittance ($U$) values are similar between glazing systems, decreasing with the application of low emissivity films (LEP35 and LEP70). For the glazing systems with reduced SHGC ($g$) values it is expected a better thermal performance. Glazing systems with high visible transmittance ($\tau_{vis}$) are less reflective, having smaller visible reflectance of the exterior ($\rho_{visE}$) and interior ($\rho_{visI}$) surfaces. The solar transmittance ($\tau_{sol}$) influences the heat gains through the glazing systems. The SCFs increase the solar reflectance of the surface they are applied on. For interior SCFs the increase on the solar reflectance of the interior surface ($\rho_{solI}$) may contribute to the heating of the indoor environment of the office room, as part of the radiation is reflected back inside. The solar reflectance of the exterior surface ($\rho_{solE}$) increases for exterior SCFs. Films with high values of $\rho_{solE}$ tend to have lower values of $\tau_{vis}$ and $\tau_{sol}$. The absorptance of the panes is influenced by the presence of SCFs as expected, with a higher absorptance of the exterior pane ($\alpha_1$) or the interior pane ($\alpha_2$) for glazing systems with exterior and interior SCFs, respectively. The $\tau_{UV}$ was significantly reduced, having possible benefits on the occupants' health and on the conservation of the offices' materials.

Parameters related to the schedules, surface construction elements, internal gains, lighting control, air renewal and VRV unit were edited on the EnergyPlus model's file. Power values of 155W [10] and 30W [10] were assumed for the desktop and the laptop computers, respectively. A reference target illuminance level of 500lx on the desk of each office was selected. The lighting control "stepped" with one step was chosen, meaning that the lights are switched on/off when the illuminance level on the desk is lower/higher than the target one. The zone mean air temperature ($T_{m,air}$), internal surface temperature ($T_{si,left}$) and external surface temperature ($T_{se,left}$) of the left side glazing systems were selected as output variables for the calibration of the model. The following periods were selected for model calibration: 1 to 7 of April (heating season) and 6 to 12 of June (cooling season). Parameters like air renewal, VRV unit working hours, occupancy and computers' schedules were edited for each office with the purpose of approximating the simulation results to the experimental data. The following commonly used statistical parameters were computed during the calibration of the numerical model in order to validate it: the Mean Bias Error (MBE), the Normalized Mean Bias Error (NMBE), the Root-Mean Square Error (RMSE) and the Coefficient of Variation of the Root-Mean Square Error (CV(RMSE)). The computed results present in Table 2 were compared to the limit values admitted in ASHRAE Guideline 14 [11]. These results are lower than the literature limits [11], apart from the NMBE results obtained for the external surface temperature of the left side glazing systems variable of offices 4.8 and 4.9. Therefore, the numerical model can be considered accurate to reproduce the performance of the offices' glazing systems and thus suitable to perform simulations of the reference glazing system with new SCFs and different solar orientations. The experimental and simulated results of the zone mean air temperature on the reference office, for the calibration periods, are represented graphically in Fig. 7.

Table 2 – MBE and RMSE obtained for the output variables, after the calibration of the model.

| | | Heating Season (1 to 7 of April) | | | Cooling Season (6 to 12 of June) | | |
|---|---|---|---|---|---|---|---|
| Office (SCF) | Error | $T_{m,air}$ [°C] | $T_{si,left}$ [°C] | $T_{se,left}$ [°C] | $T_{m,air}$ [°C] | $T_{si,left}$ [°C] | $T_{se,left}$ [°C] |
| 4.7 (Ext.) | MBE [°C] | -0.88 | -1.20 | -1.62 | -1.08 | -1.44 | -1.99 |
| | NMBE [%] | -3.38 | -6.21 | -9.44 | -3.97 | -5.40 | -7.64 |
| | RMSE [°C] | 1.05 | 2.08 | 3.70 | 1.52 | 2.35 | 4.19 |
| | CV (RMSE) [%] | 4.29 | 10.85 | 21.66 | 5.61 | 8.86 | 16.17 |
| 4.8 (Int.) | MBE [°C] | 0.06 | -1.01 | -2.02 | -0.52 | -1.15 | -2.20 |
| | NMBE [%] | 0.49 | -4.46 | -11.15 | -1.84 | -3.94 | -8.23 |
| | RMSE [°C] | 0.96 | 4.34 | 4.06 | 1.23 | 4.06 | 3.70 |
| | CV (RMSE) [%] | 4.60 | 20.04 | 22.60 | 4.41 | 13.94 | 13.89 |
| 4.9 | MBE [°C] | -0.20 | -1.56 | -1.83 | -0.22 | -1.48 | -2.20 |
| | NMBE [%] | -0.91 | -7.40 | -10.66 | -0.77 | -5.15 | -8.40 |
| | RMSE [°C] | 1.58 | 3.55 | 3.55 | 1.29 | 3.61 | 3.53 |
| | CV (RMSE) [%] | 7.11 | 16.92 | 20.75 | 4.46 | 12.58 | 13.49 |

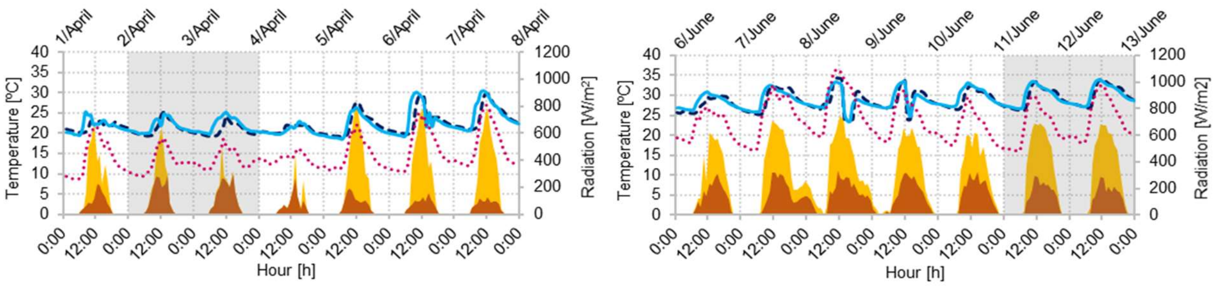

Fig. 7 - Comparison of the measured and simulated zone mean air temperature of the reference office without SCF, in the selected periods of the heating (left) and cooling (right) seasons.

## 4. Results and discussion

The reference office model has undergone some modifications to support the performance evaluation process of the glazing systems. The assumed working hours were 09h to 18h from Monday to Friday. The reference target illuminance of 500lx was maintained but the lighting control “CountinousOff” was selected to allow to obtain only the lighting needs to achieve the target value. The laptop computer was assumed to be on during working hours and off the remaining hours. The desktop computer was assumed to be on during working hours and in suspend mode (consuming 20% of power [10]) otherwise. The venetian blinds were removed from the simulation to obtain results not dependent on shading control.

### 4.1. Thermal and Optical Performance of Glazing Systems with SCFs

The annual cumulative frequency of comfortable levels of indoor illuminance, glare and temperature during working hours was analysed in order to evaluate the thermal and optical performance of the glazing systems. The VRV unit was not considered so that the results could be independent from temperature control. The zone mean air temperature, daylighting reference point 1 glare index and daylighting reference point 1 illuminance, where point 1 is located in the centre of the desk, were selected as output variables of the simulation. Glare was calculated by EnergyPlus using the daylight glare index (DGI). Illuminance levels higher than 500lx were considered desirable, however extreme values may have a negative effect on the visual comfort of the occupants. For daylight glare index, the comfort interval from 16 to 22 was considered. Indoor temperature values between 18°C and 25°C were assumed to be comfortable.

The maximum values of illuminance (20 389lx), glare (DGI = 48.24) and temperature (50.68°C) were reached with the reference glazing system without SCF due to its high $\tau_{vis}$ (= 81%) and $g$ (= 0.76) compared to the cases with SCFs. Low reflective exterior PR90EXT ($\tau_{vis}$ = 79%) film had a quite similar optical performance to the one of the reference glazing. The interior LEP70 film’s thermal performance is the closest to the one of the reference glazing, due to the glazing with SCF’s $\tau_{sol}$ (= 38%) and $\rho_{solI}$ (= 29%). The high reflective exterior RHE20SIERHPR ($\tau_{vis}$ = 16%; $g$ = 0.15) film significantly reduced the maximum values of indoor illuminance, glare and temperature, having as maximum values 3 989lx, DGI = 43.96 and 35.36°C.

The annual cumulative frequency of levels of the abovementioned variables (illuminance, glare ad temperature) during working hours is present in Table 3. Considering the reference glazing system, desirable levels of indoor illuminance were achieved during 80% of working hours, but, on the other hand, comfort levels of indoor glare and temperature had a low cumulative frequency of about 5%. In the presence of the exterior RHE20SIERHPR film, the highest annual cumulative frequency of comfortable glare (43%) and temperature (41%) levels was obtained.

Table 3 – Annual cumulative frequency (%) of levels of indoor illuminance, glare and temperature during working hours in the reference office, for the considered glazing systems, sorted by increasing visible transmittance, for Lisbon's typical meteorological year.

| | | Illuminance [%] | | Glare [%] | | | Temperature [%] | | |
|---|---|---|---|---|---|---|---|---|---|
| | P[1] | < 500 lx | ≥ 500 lx | < 16 | 16 - 22 | > 22 | < 18 °C | 18 – 25 °C | > 25 °C |
| RHE20SIERHPR* | E | 71.07 | 28.93 | 19.15 | 43.46 | 37.39 | 9.87 | 40.60 | 49.53 |
| R35SISRHPR* | I | 58.12 | 41.88 | 11.88 | 20.86 | 67.26 | 0.90 | 24.57 | 74.53 |
| LEP35 | I | 52.91 | 47.09 | 10.21 | 14.66 | 75.13 | 0.98 | 26.50 | 72.52 |
| RE35SIARXL | E | 51.92 | 48.08 | 10.00 | 14.49 | 75.51 | 1.62 | 36.20 | 62.18 |
| PR40EXT | E | 48.16 | 51.84 | 8.64 | 11.79 | 79.57 | 1.67 | 36.07 | 62.26 |
| RE35NEARXL | E | 42.21 | 54.79 | 8.25 | 11.45 | 80.30 | 0.77 | 26.71 | 72.52 |
| R50 | I | 40.30 | 59.70 | 8.03 | 10.90 | 81.07 | 0.30 | 15.34 | 84.36 |
| Silver50Xtra | E | 39.74 | 60.26 | 8.03 | 10.90 | 81.07 | 1.11 | 32.01 | 66.88 |
| Titan50Xtra | E | 36.37 | 63.63 | 7.18 | 9.91 | 82.91 | 0.81 | 27.82 | 71.37 |
| Titan50Xtra | E | 36.37 | 63.63 | 7.18 | 9.91 | 82.91 | 0.81 | 27.82 | 71.37 |
| LEP70 | I | 26.58 | 73.42 | 6.16 | 7.09 | 86.75 | 0.00 | 9.83 | 90.17 |
| PR70EXT | E | 25.77 | 74.23 | 6.15 | 6.88 | 86.97 | 0.94 | 30.90 | 68.16 |
| PR90EXT | E | 20.13 | 79.87 | 5.51 | 5.51 | 88.98 | 0.17 | 16.03 | 83.80 |
| Without SCF | | 19.87 | 80.13 | 5.47 | 5.38 | 89.15 | 0.00 | 5.26 | 94.74 |

* SCFs present during the experimental campaign

[1] Position: I - Interior; E - Exterior

### 4.2. Energy Performance of Glazing Systems with SCFs

The annual energy needs, final and primary energy consumption, peak demand load and $CO_2$ emissions were computed and analysed to evaluate the energy performance of the glazing systems. The VRV unit was assumed to be on during working hours, with the following set points: 20°C (heating) and 24°C (cooling). As expected, the lighting energy needs increased for more reflective glazing systems and the cooling needs decreased significantly for glazing systems with exterior films and low $g$ values. The annual energy use, in kWh/year per square meter of floor, for the glazing systems is shown in Fig. 8. Annual lighting consumption of 4.62kWh/m$^2$/year, VRV unit consumption of 21.84 kWh/m$^2$/year and total consumption of 26.46kWh/m$^2$/year were obtained for the reference glazing system without SCF. Due to the VRV unit's high efficiency (SCOP = 7.98; SEER = 4.43), the lighting energy needs have a higher influence in the annual energy needs. Although RHE20SIERHPR, present during the experimental campaign, has shown a large impact on the reduction of the cooling energy needs, it presents the smallest reduction of the annual total energy use since it corresponds to the glazing system with the lowest $\tau_{vis}$ (= 16%) and therefore with the highest lighting energy use. By applying the exterior PR70EXT film, a total consumption of 16.35kWh/m$^2$/year was achieved, corresponding to the lowest obtained value.

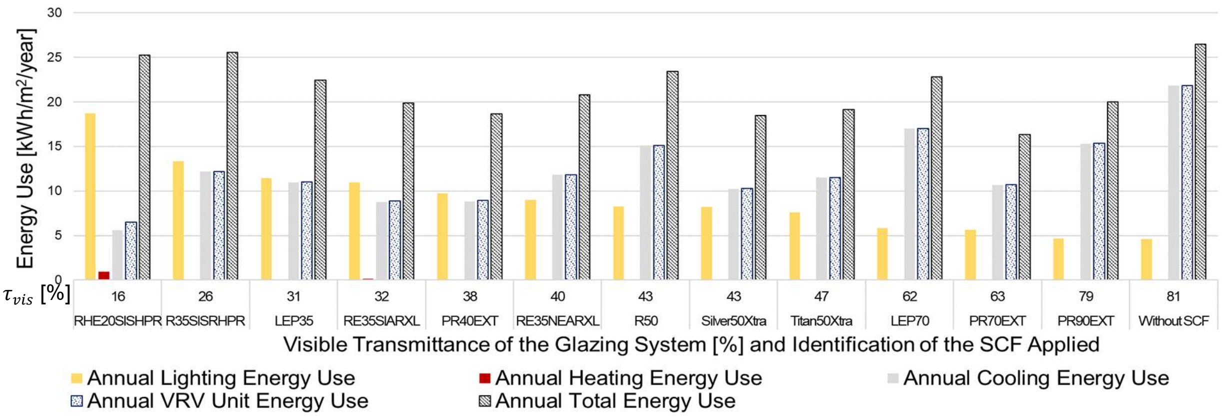


Fig. 8 – Annual energy use, in kWh/year per square meter of floor, for the considered glazing systems, sorted by increasing visible transmittance ($\tau_{vis}$ [%]).

When evaluating the influence of the glazing systems' solar orientation on the energy consumption, the lowest values (intermediate floor: 10.92kWh/m$^2$/year; top floor: 11.42kWh/m$^2$/year) were achieved with the application of the exterior PR70EXT film on a west oriented window. This evaluation was carried out for the building's top floor (case study) and intermediate floor by simulating all the orientations of the building's exterior glazed façade: southeast (case study), south, west and northeast. The VRV unit energy consumption varied between floors, with the top floor having smaller cooling and higher heating energy consumptions than the intermediate floor, indicating that the heat losses through the flat roof are higher than the heat gains.

The energy and cost savings and the peak demand load and $CO_2$ emissions reductions resulting from the application of the SCFs on the case study's glazing systems are present in Table 4. The lighting, VRV unit and computers electricity consumption was considered for the peak demand load calculation. When determining the $CO_2$ emissions, only the ones resulting from the consumption of primary energy were regarded, the ones from the SCFs' production, transportation and application not being considered. Annual electricity cost of 68.71€/year, peak demand load of 50.82kW and $CO_2$ emissions of 263kg$_{CO2}$/year were obtained for the reference glazing system without SCF. The highest electricity saving (38.20%), electricity cost saving (38.17%) and $CO_2$ emissions reduction (38.02%) were achieved in the presence of the exterior PR70EXT film. The most significant peak demand load reduction (68.83%) was obtained when applying the exterior RHE20SIERHPR film.

Table 4 – SCFs' cost of application (€/m$^2$), electricity saving (kWh/m$^2$/year and %), electricity cost saving (€/year and %), peak demand load reduction (kW and %) and $CO_2$ emissions reduction (kg$_{CO2}$ and %) compared to the reference glazing system without SCF obtained for the considered glazing systems with SCFs, sorted by increasing visible transmittance.

| SCF | Pos. | SCF cost | Electricity saving | | Electricity cost saving | | Peak demand load reduction | | $CO_2$ emissions reduction | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | [€/m$^2$] | [kWh/m$^2$/year] | [%] | [€/year] | [%] | [kW] | [%] | [kg$_{CO2}$/year] | [%] |
| RHE20SIERHPR* | Ext. | 18.00 | 1.20 | 4.54 | 3.14 | 4.57 | 35.05 | 68.83 | 12 | 4.56 |
| R35SISRHPR* | Int. | 13.00 | 0.92 | 3.49 | 2.46 | 3.58 | 15.56 | 30.57 | 10 | 3.80 |
| LEP35 | Int. | D[2] | 4.00 | 15.13 | 10.38 | 15.11 | 14.92 | 29.30 | 40 | 15.21 |
| RE35SIARXL | Ext. | 22.00 | 6.59 | 24.96 | 17.21 | 25.05 | 25.01 | 49.12 | 66 | 25.10 |
| PR40EXT | Ext. | 57.00 | 7.80 | 29.47 | 20.22 | 29.42 | 23.8 | 46.74 | 77 | 29.28 |
| RE35NEARXL | Ext. | 31.00 | 5.64 | 21.32 | 14.62 | 21.27 | 16.87 | 33.13 | 56 | 21.29 |
| R50 | Int. | 13.00 | 3.08 | 11.59 | 8.06 | 11.73 | 9.30 | 18.27 | 31 | 11.79 |
| Silver50Xtra | Ext. | NA[1] | 7.98 | 30.15 | 20.76 | 30.22 | 21.04 | 41.33 | 79 | 30.04 |
| Titan50Xtra | Ext. | NA[1] | 7.34 | 27.70 | 18.99 | 27.63 | 17.09 | 35.16 | 73 | 27.76 |
| LEP70 | Int. | D[2] | 3.64 | 13.74 | 9.43 | 13.72 | 4.12 | 8.09 | 36 | 13.69 |
| PR70EXT | Ext. | 57.00 | 10.11 | 38.20 | 26.23 | 38.17 | 19.34 | 37.98 | 100 | 38.02 |
| PR90EXT | Ext. | 34.00 | 6.45 | 24.37 | 16.8 | 24.45 | 10.36 | 20.36 | 64 | 24.33 |

* SCFs present during the experimental campaign

[1] Not Available; [2] Discontinued

## 5. Multicriteria Analysis of the Selection of SCFs

From the analysis of the results, the performance of a SCF varies depending on the criteria (comfort, energetic, economic, environmental) used to make the selection. Therefore, a multicriteria analysis using the Analytic Hierarchy Process, developed by Saaty [12], was applied to help on the selection of the SCF with the best global performance, having as selection criteria: investment cost (C1); annual electricity cost (C2); annual cumulative frequency of thermal discomfort (C3); annual cumulative frequency of glare uncomfortable levels (C4); and annual $CO_2$ emissions (C5). The investment cost (C1) consists on the sum of the SCFs cost (Table 4) and the cost of application (considering 8€/m$^2$ per film, as provided by a window film application company). In order to compute the criteria's weights, a matrix of pairwise comparison of the criteria (Table 5), using the Saaty Fundamental Scale [12], was created and then normalized. The obtained weights were: 0.064 (C1), 0.118 (C2), 0.195 (C3), 0.195 (C4) and 0.429 (C5), meaning that the smallest importance was assigned to C1, the highest importance to C5 and an equal importance to the comfort criteria C3 and C4. The eigenvalue ($\lambda_{máx}$), consistency index (CI) and consistency ratio (CR) were calculated to evaluate the consistency of the abovementioned comparison matrix, the obtained results being showed in Table 6. After checking the consistency (CR = 0.082 < 0.1), the alternative scores were obtained by summing, for each alternative, the product of its normalized value in a certain criterion by the weight of the same criterion, for all the selection criteria. The highest score, of 0.695, was obtained for the spectrally selective film PR70EXT and the smallest score, of 0.064, for the reference glazing system (without SCF).

Since the preference values on the pairwise comparison are attributed by the decision maker (making them subjective), a sensitivity analysis was applied to better understand the influence of the criteria's weights variation on the selection of the alternative with the best global performance. For C1, PR70EXT showed to be the best alternative for weights smaller than 0.20, the reference glazing for weights higher than 0.56 and RE35SIARXL for weighs between these values. PR70EXT is always considered to be the best alternative for any weight attributed to C2. For C3, PR70EXT was obtained as the best alternative for weights smaller than 0.46, the RHE20SIERHPR for weights higher than 0.60 and PR40EXT for weighs between these values. For C4, PR70EXT is the best alternative for weights smaller than 0.34 being replaced by RHE20SIERHPR for higher weights. For C5, the opposite happens, RHE20SIERHPR being the best alternative for weights smaller than 0.25 and then replaced by PR70EXT for higher weights, as shown in Fig. 9.

Table 5 – Matrix of pairwise comparison of the selection criteria.

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| C1 | 1 | 1/4 | 1/3 | 1/3 | 1/4 |
| C2 | 4 | 1 | 1/3 | 1/3 | 1/4 |
| C3 | 3 | 3 | 1 | 1 | 1/3 |
| C4 | 3 | 3 | 1 | 1 | 1/3 |
| C5 | 4 | 4 | 3 | 3 | 1 |
| Total | 15 | 45/4 | 17/3 | 17/3 | 13/6 |

Table 6 – Results obtained during the consistency analysis.

| $\lambda_{máx}$ | CI | CR |
|---|---|---|
| 5.369 | 0.092 | 0.082 |

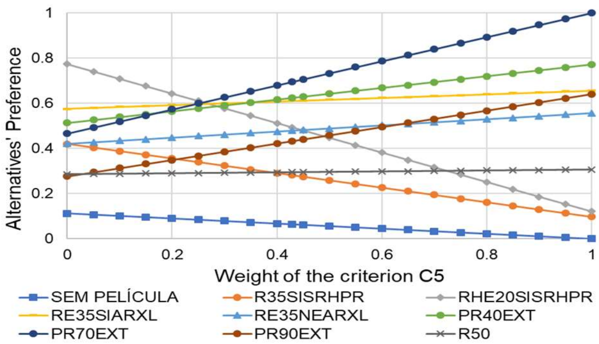


Fig. 9 – Influence of the weight of the criterion C5 (annual $CO_2$ emissions) on the alternatives' preference.

## 6. Conclusions

In order to evaluate the thermal, optical and energy performance of different types of SCFs applied on glazing systems, three adjacent offices in IST, in Lisbon, were considered as case study. A numerical simulation was developed using EnergyPlus and then calibrated with experimental data. Moreover, the results were used in a multicriteria analysis to select the SCF with the best global performance.

The results of the numerical simulation agree with the ones from previous studies [2-7]. The SCFs reduced the indoor illuminance levels and the heat gains through the glazings, originating an increase on the lighting energy needs and a decrease on the cooling energy needs and peak demand load. The lighting energy increase is more noticeable for high reflective films. Due to the reflection of radiation back to the office, interior films had the worst thermal performance compared to exterior films. A significant decrease in cooling needs and peak demand load was obtained for exterior films with a low $g$ value.

The RHE20SIERHPR ($\tau_{vis}$ = 16%; $g$ = 0.15) film allowed to achieve comfort daylight glare index and indoor temperature values during, respectively, 43% and 41% of working hours, which constitutes a large improvement of the indoor comfort conditions when compared to the poor results of the reference glazing (without SCF), where comfort values were met only during 5% of working hour. An annual lighting energy use of 4.62kWh/m$^2$/year, VRV unit energy use of 21.84kWh/m$^2$/year, $CO_2$ emissions of $263\mathrm{kg}_{\mathrm{CO_2}}$/year and a total energy use of 26.46kWh/m$^2$/year, corresponding to a cost of 68.71€/year, were obtained for the reference glazing system ($\tau_{vis}$ = 81%; $g$ = 0.76). PR70EXT ($\tau_{vis}$ = 63%; $g$ = 0.40) reduced the annual $CO_2$ emissions, total energy use and cost by 38%, originating an annual lighting and VRV unit energy use of 5.66 and 10.69kWh/m$^2$/year, respectively. The peak demand load of 50.92kW for the reference glazing was reduced by 69% in the presence of RHE20SIERHPR. When considering the different exterior façade orientations of the building, the best energy performance was obtained with PR70EXT installed on a West oriented window.

By applying a multicriteria analysis to help on the selection of the SCF with the best global performance, PR70EXT with a score of 0.695 was obtained as the best alternative for the preference values attributed to the chosen criteria. The best alternative varies according to the criteria's weights, RHE20SIERHPR being considered the best alternative for bigger weights in the comfort criteria.

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