

Solar Control Window Films Simulation

Júlia Oliveira Pereira

October 2015

Abstract

Window films are major in adapting a building's glass properties on different parameters. Due to the extreme climatic conditions, and in order to reduce the use of greenhouse gases through energy consumption, this dissertation explores the impact of the use of a solar control window film in terms of energy efficiency in buildings. A sensitivity modular analysis was conducted on two adiabatic compartments, in a building located in Lisbon. Measurements and comparisons were made on four different situations of the room, considering its thermal and energetic performances in actual working conditions. The resulting observations carried out after the statistically analysis revealed the potential that solar control films have in decreasing the energy consumption of a building as well as in reaching thermal comfort in its interior, especially when it comes to buildings in rehabilitation situations

Keywords: Solar Control Window Films, Building energy simulation, EnergyPlus, Energy consumption reduction

1. Introduction

The Industrial Revolution, along with the sudden growth of the population and the economy, has been intensifying the greenhouse gases concentration (GHG) in the atmosphere due to the burning of fossil fuels and human activities. The GHG can elevate the average temperature of the Earth's surface through radiation, causing Global Warming.

The resulting climate extremes detected in the past century together with the modern architecture of glass façades and its loads of sunlight, determine the meaning and increased use of the thermal systems in buildings. Due to the high energy consumption of a building's heating, ventilation and air conditioning (HVAC) systems, that surrounds approximately 37% of its energy consumption, there has been great awareness on a building's energy efficiency. In this context, the European Parliament approved the 2012/27/UE directive that reinforces the European target of a 20% improvement in the EU's energy efficiency by 2020.

The present dissertation addresses the efficiency of the application of interior as well

as exterior solar control window films in a building located in Portugal.

2. Solar Control Window Films

According to the EN 15755-1 norm, an adhesive backed polymeric filmed glass is defined as a glass with its technical features and performance changed by the addition of an adhesive polymeric film. It is also known as a window film.

Currently, there is a wide offer of solar control window films with various glass changing purposes such as solar factor (g), visible transmittance (T_{vis}), emissivity (ϵ), UV transmittance (UVt), privacy, aesthetics, behavior towards an impact, security, electromagnetic shielding and glass surface protection.

The importance beneath the use of a solar control window film lays in the lack of sunlight and thermal isolation of a plain glass. An immense solar radiation may damage objects like furniture and may turn the indoor environment very uncomfortable, by increasing its temperature. The thermal discomfort

caused by heat or cold has great power on dissatisfying the people inside the building.

Nevertheless, thermal comfort was not the main issue beneath the birth of the first glass film; it was, however, the energy efficiency of the solar radiation. The first glass films shielded almost all electromagnetic radiation, which reduced pretty much the indoor visibility, leading to an increase of energy consumption in lightening, ventilation and air conditioning. Also, they excessively absorbed heat, elevating glass temperature so much that sometimes the glass cracked.

These handicaps countered the film concept and encouraged years of investigation and development of new materials with less disadvantages.

The solar control window films were most developed in the 70's with the incorporation of polyester fibers.

Though there are many kinds of window films, as we've seen before, this study frames the ones mostly used in the construction industry in Portugal:

Solar Control (g): decreases the solar factor, contributing to the reduction of the energy consumption indoors;

UV Protection: shields all the UV radiation, securing the indoor furniture and objects from damage;

Low Emissivity: improve the glass thermal isolation and the indoor thermal comfort, contributing to the reduction of the energy consumption;

Glare Reducing: improve the indoor working conditions by reducing glare and reflections;

Protection and safety: absorbs high energy impact, holding together glass shrapnel when cracked;

Protection: delays and/or prevents the entrance of strange people. It can also nullify outdoor visibility, maintaining indoor privacy;

Anti-graffiti: transparent and used as an outer layer for vandalism acts;

Decorative: used for aesthetic matters.

3. Solar Control Window Film features

The solar control window film can modify the glass solar factor through various parameters such as transmission, reflection, absorption, UV and visible light transmission.

It features layered membranes of different materials: Disposable protection (polyester film that protects the adhesive from possible contaminations); Adhesive, which can be

pressure sensitive adhesive (PSA) or water activated adhesive; High performance UV resin (shields the UV radiation); Polyester (gives the optical, thermal, mechanical, physical and chemical characteristics to the film). It's very durable, resistant, and flexible. The polyester layers, connected through lamination processes, improve the film ability to absorb or reject radiation. Additionally, with the incorporation of metallic oxides, this layer can be more versatile and precisely reflect different types of radiation; Rolling adhesive (used to join together the polyester layers through rolling processes); Metal (the metal, usually the aluminum, is incorporated in the polyester membrane and has the ability of rejecting light from low 15% to high 70%); Anti-scratch protection (protects the film from wearing out).

2.1 Solar Control Window Film Simulations

Several studies have been conducted in residential and commercial buildings to determine the impact of a solar control window film in a glass façade. The main issue found on studies exploring commercial buildings (Hanita Coatings, Solar Gard) was the high amount of energy transmitted through plain glass windows, which led to the increase of the temperature inside the building causing great discomfort among the workers at their working places, negatively affecting their output. One of the studies (Solar Gard) even recognized the lack and, at times, absence of ventilation and air conditioning on the areas with the highest temperatures. On these cases, a solar control window film was applied to an extent of 4.000 m² (Hanita Coatings) and 1.000 m² (Solar Gard). Apart its differences in matters of extension and thermal properties, on both cases the rejection of radiation (from 32% up to 64%) and its absorption (26% a 45%) led to an energy reduction that varied from 64% to 83%.

These solar control alternatives provided a temperature decrease to 20°C, compared to the same month of the year before (June), and an estimated annual economy of €20.000 on air conditioning. (Hanita Coatings) Along with these results and the rejection of 61% of heat, the film also maximized the light transmittance by reducing the use of solar curtains. (Solar Gard) On both cases, the cooler atmosphere inside the building and among workers at their working place improved with greater thermal

comfort, hence, their productivity got better. (Hanita Coating, Solar Gard)

The installation of the window film lasted for only two weeks without causing any working disorder.

In terms of residential buildings, the main issue besides the thermal discomfort, was maintaining the view and reducing the amounts of glare and brightness inside the building as well as minimizing the expenditures due to lighting and cooling requirements. (Solar Gard, Lluma)

After the film application, which reduced the energy by 65% in one case (Lluma) and by 54% on another (Solar Gard), rejecting light from 16% to 26%, and absorbing it from 49% to 54%, the building's interior atmosphere became cooler and, thus, much more comfortable. Furthermore, the view quality got preserved and the building's interior objects got protected from UV rays. Finally, it is important to point out the savings in air conditioning as well as the reduction in glare and brightness.

4. Simulation Software – Optics6 and Window

The understanding of the thermal and optical properties of a glass façade system is crucial to an efficient energy performance of a building. As a result, the development and update of the software programs that treat this type of data is decisive to the construction industry on structuring buildings with better energy-efficient designs.

The American Optics6 software, which has its contents approved by the International Glazing Database (IGDB), can create countless simulations regarding window films available in the market. In order to submit a new film, all the properties tests have to respect the National Fenestration Rating Council norms.

On another hand, Window software is an interface developed by Microsoft Windows™ that calculates the thermal and optical parameters of the film, also according to the ASHRAE SPC142, ISO15099, and the National Fenestration Rating Council norms.

Both are free and available on the internet.

3.1 Window 7.3.8 e Optics6 software validation

Currently, as there are many calculation programs available for all kinds of materials, its use in scientific documents and studies must be thorough and equated with accredited

companies. The Optics6 and Window 7.3.8 programs were developed by official laboratories with worldwide recognition, following specific norms from Europe or the United States.

Through the elaboration of the present document, and in all study cases, the results were obtained by these programs and always confronted with the technical data provided by the company. Since those results did not significantly differ from each other, the validation of these programs has, therefore, been proven.

3.2 Study cases: solar control window films

The purpose of this study is to understand the optical impact of window films. Taking that into account, there was a selection of many types of glass, with different thicknesses, laminated glass, double glass and glass with metal coating. To realize the effect of the film on the optical properties of a glass, it was selected seven kinds of films with interior application and six exterior films.

3.3 Interior solar control window films study cases: results review

By resorting to the Optics5 and Window 7.3.8 programs, it was possible to determine the solar factor, the heat transfer coefficient and the visible transmission from the different kinds of glass with the films applied on its interior surface.

3.3.1 Solar Factor Influence (gráficos e tabelas?)

The solar factor results were obtained for simple glass (A to C) with three different thicknesses (4mm, 6mm and 8mm) and for laminated glass (D to H) with four distinct measurements (4x4mm, 6x6mm, 8x8mm, 8x4mm and 8x6mm). It was also measured the variation in the solar factor with the application of the films on the studied glasses.

The values were obtained through Window 7.3.8 and Optics5 software programs.

Results analysis for g factor in simple and laminated glass with and without the application of seven thin film coatings on its interior surface:

- R20 SI SR HPR and R20 SI SR HPR films are the best in reducing the solar factor (in

4mm simple glass), with high rejection properties which provides great performance in heat gain and cooling expenses;

- N1040 SR CDF and LEP 70 SR CDF are the worst in reducing solar factor (in 4mm simple glass). With a more neutral color, these films balance the heat rejection, UV transmittance without compromising, too much, natural light transmission;
- In simple glass, as the thickness increases, smaller is the ability of the film in reducing the solar factor, though this difference is not significant (1-4%);
- Comparing C and D cases, with a reduction between 2 to 3% in the solar factor variation, it is possible to conclude that the lamination adhesive has little influence in the film performance;
- Equating E and G outcome, one can reason that the results are equal for all study objects, which strengthens the premise that the film's solar factor influence in laminated glass depends, exclusively, on the glass thickness, and not on the laminated adhesive.

Results analysis for g factor in double glass with and without the application of seven thin film coatings on its interior surface:

- The influence of the film in the g factor decreased significantly, compared to the results obtained in simple and laminated glasses;
- Comparing I, C and D cases, it appears that the g factor influence decreases from 6 to 11% in simple glass and from 3 to 8% in laminated glass;
- The results for air-chamber glasses and combined glasses (90% air-chamber and 10% argon) were very similar (less than 1% variations). This indicates that an interior thin film performance on the g factor of a glass does not change with the air-chamber fill.

Results analysis for g factor in double glass with solar protection with and without the application of seven thin film coatings on its interior surface:

- The performance of the thin film coatings in this type of glass is very low, when compared to similar glass without solar protection;
- Counterweighing P, I and M cases, it is possible to find that the films have a poor

performance when added to a double glass with solar protection, no matter its thickness;

- The more neutral films, N1040 SR CDF and LEP70 SR CDF, don't present a significant variation in decreasing the g factor;
- The results obtained on both solar protection double glasses were similar, concluding that the film performance is not influence by the applied solar protection.

3.3.2 Visible Transmittance Influence T_{vis}

The Visible Transmittance Influence results were obtained in cases from A to U, with and without the addition of an interior thin film coating.

Results analysis for Visible Transmittance Influence, T_{vis} , in simple and laminated glass with and without the application of seven thin film coatings on its interior surface:

- The visible transmittance influence of the glass, after applying the film, can vary from film to film, from very low numbers, such as the R 20 SI SR HPR film (0,1 to 0,6), to higher values, like the ones given by the LEP70 SR CDF film (0,5 a 0,7);
- Since there is a small variation range between all study cases, glass type has very low influence on the visible transmittance;
- The results obtained in every subject are very close to the ones presented by the traders catalogs.

3.3.3 Heat Transfer Coefficient, U

The heat transfer coefficient does not change with the addition of an interior thin film coating. This is due to the fact that the film thickness is much lower than the glass's.

3.4 Exterior solar control window films study cases: results review

By using Optics5 and Window 7.3.8 software programs, it was possible to determine the solar factor, the heat transfer coefficient and the visible transmission from the different kinds of glass with the films applied on its exterior surface.

3.4.1 Solar Factor Influence, g

The solar factor results were obtained for simple glass (A to C) and for laminated glass (D

to H). It was also measured the variation in the solar factor with the application of the films on the studied glasses.

The values were obtained through Window 7.3.8 and Optics5 software programs.

Results analysis for g factor in simple and laminated glass with and without the application of six thin film coatings on its exterior surface:

- Like its interior equivalent, RHE20 SI ER HPR film is the most effective in decreasing the g factor in simple glass (4mm);
- The g factor influence of the film lowers as the glass thickness increases;
- PR70EXT and NHE1035 ER HPR films are the worst in decreasing g factor;
- Comparing C and D cases, one can verify that there is a reduced ability of the film in decreasing the g factor. These values are much close to the ones obtained in interior films;
- Comparing E and G cases, it is to reason that the performance of the film in reducing the g factor depends, exclusively, on the glass thickness.

Results analysis for g factor in double glass with and without the application of six thin film coatings on its exterior surface

- The film performance, in reducing the g factor, is much higher in double glass, when compared to the same reduction in simple and laminated glasses;
- Comparing the I, L, M and O glasses, one can determine that the glass thickness has little influence in the g factor;
- The values obtained for air-chamber and combined glasses (90% air-chamber and 10% argon) are very much alike (less than 1% variation), which implies that the exterior film's performance in the g factor is not determined by the air-chamber fill.

Results analysis for g factor in double glass with solar protection with and without the application of six thin film coatings on its exterior surface

- As verified in the interior film study results, the performance of the thin film coatings in this type of glass is very low, when compared to similar glass without solar protection;
- Comparing P and S with the I and M cases, one can verify that the films have a much

lower performance in the double glass with solar protection, rather than in the plain double glass. The low performance of the film registered in the 6x6m and 8x8m glass is of the same order of magnitude as that observed in the 4x4m glass;

- Analyzing the influence of the solar protection added in the 4x4m, 6x6m and 8x8m glass, it is possible to determine that the exterior film's influence in reducing the g factor is determined by the kind of solar protection added.

3.4.2 Visible Transmittance Influence, T_{vis}

The Visible Transmittance Influence results were obtained in cases from A to U, with and without the addition of an interior thin film coating.

Results analysis for Visible Transmittance Influence, T_{vis} , in simple and laminated glass with and without the application of six thin film coatings on its interior surface:

- The visible transmittance influence of the glass, after applying the film, can vary from film to film from very low numbers to higher values;
- PR70EXT film presents T_{vis} variation values between 11 and 21%, which demonstrates that its performance is influenced by the type of glass. Nevertheless, the results obtained in all subject films of this study showed very little T_{vis} variation, which concludes that the T_{vis} reduction is similar in every glass subject.

3.4.3 Heat Transfer Coefficient, U

As concluded in the interior film's study cases, the heat transfer coefficient does not change with the addition of an exterior thin film coating. This is due to the fact that the film thickness is much lower than the glass's.

5. Study Office and Experimental Campaign

This study involves field measurements on the solar control window films efficiency in two matching cellular offices located on the east façade of the second floor of the Civil and Architecture Pavilion of Instituto Superior Técnico, built in 1993 in the centre of mild Lisbon city.

The two adjacent offices (rooms A and B) are identical in dimensions, geometry, orientation

and glass façade area. It was applied a solar

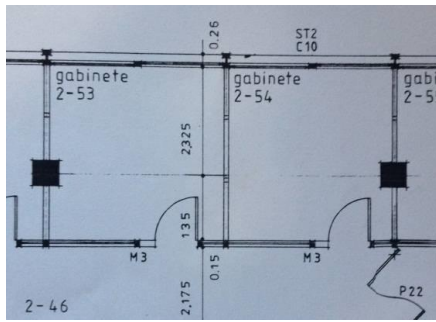


Figure 1 The rooms A and B designs

control film on the windows of room A, whereas the ones in room B were kept without the film.

5.1 Geometric model 3D Sketchup

In order to elaborate the geometric model of the room, it was used the room's interior measurements, ascertained with the aid of a measure tape. The total area was about 13,5 m². Both rooms were considered adiabatic. The wall and window are on the East side, in contact with the exterior, therefore, exposed to the climate changes. The ceiling, 3.15m high, offers no thermal resistance. Regarding the shading conditions, a garden shades the East façade, so does the extension of the superior and inferior slabs. These geometrical characteristics were simulated on the *BuildingSurface:Detailed* parameter of the *ThermalZones and Surfaces* of the IDF Editor. By the way the cubicle was designed, it was necessary to define an angle of 270° to make the *SketchUp* North coincident with the true North.

5.2 Materials

The materials characteristics of the offices are defined on table 1.

Material	Ceramic brick 11	Plaster of 2 cm	Reinforced concrete <1% of armature	Ceramic brick 7	Pressed cork agglomerate	Chaferpaving flags	Slabs
Rough	rough	rough	Average	rough	Average	Average	Average

Thickness (m)	0.11	0.02	0.08	0.07	0.004	0.04	0.4
Thermal conductivity (W/(m.°C)) [1]	0.407	1.3	2.0	0.368	0.065	0.77	1.944
Density (kg/m ³) [1]	630*	1900	2400	818*	400	1900	2560*
Specific Heat (J/(kg.°C))	960	1000	940	960	170	960	940
Heat absorption	0.9	0.9	0.5	0.9	0.9	0.9	0.9
Solar absorption	0.5	0.8	0.7	0.5	0.4	0.5	0.7
Visible absorption	0.76	0.65	0.7	0.7	0.7	0.7	0.7

Table 1 Office structure material characteristics.

5.3 Office elements

The materials used on the office constitution elements are:

- External wall: 11 cm brick stuck double wall, coated with 2cm plaster on the inside, 9cm airbox and a 8cm reinforced concrete pre-fabricated panel (figure2);
- West Interior Wall: 7cm brick stuck wall, coated with 2cm plaster on both sides (figure 3);
- North and South Interior Walls: 1cm double plasterboard with an air layer of 10cm (figure 4);
- Roofing and flooring: 40cm slabs with 4cm chafers slabs, and 4mm pressed cork agglomerate finishing;
- Window: 6mm simple glass with an aluminum frame, without thermal cutting.

5.4 Experimental Procedure

The measurements performed with the purpose of assessing the energy efficiency of the solar control film on the East glass façade of the office were performed on three experimental campaigns in spring, summer and winter.

6. EnergyPlus

EnergyPlus is one of the most developed energy analysis and thermal load simulation programs, being selected as the simulation platform for the analysis of the Solar Control Window Films Simulation. This software was born in the United States of America from two other simulation programs: BLAST (Building Loads and Analysis and System Thermodynamics) and DOE-2. Both were written in FORTRAN and had some technical restrictions, such as the inability to properly account feedback for HVAC calculations into the overall energy balance analysis. These limitations led to inaccurate space temperature appraisal.

EnergyPlus was, hence, created in a pursuit of bringing together the best features from each code in a modular structure that simplifies the development and incorporation of a wide variety of new features. This program models heating, cooling, lightning, ventilation and other energy flows based on indoor and outdoor environmental conditions. As major handicap, the EnergyPlus has some limitations in defining the geometry of the building, requiring help from a coordinate system. For this matter, the OpenStudio Plug-in along with the Google SketchUp drawing tool grants the user the possibility of quickly generating geometry for EnergyPlus.

In order to manage a simulation, two input files are required: a building input data file (IDF) that

includes the characteristics of the study case, and a weather data file (EPW), which has the local climate information.

7. Window films: Energy Performance Analysis

The statistical analysis was conducted using the SPSS 22.0 (*Statistical Package for the Social Sciences*) program, which enables the work of information for analytical application, prospecting data and text for statistical purposes.

To simplify the data analysis, the window films used in this study were grouped according to their performance in reducing the g factor and the visible transmittance.

Group	Interior Window Films	Exterior Window Films	g	T_{vis}
1	R20, R35, N1020, Lep35	R20, R35, N1020	<0,45	<0,30
2	R50, N1040, Lep70	R50, N1040	\geq 0,45	\geq 0,30
3	-	PR70	0,53	0,71

7.1 Heating season analysis

The heating season was held from November 1st to April 10th.

Table 1 - Daily Averages of the lighting power consumption (Consumption), illuminance (illuminance), of the interior temperature (temperature) and heating electricity consumption (heating expenses) for the heating season with the application of interior window films

	Without blind		With blind		Group 1		Group 2		Sig.
	M	Dp	M	Dp	M	Dp	M	Dp	
Heating season									
Consumption	5,12 ^{a)}	24,17	10,98 ^{b)}	32,60	14,01 ^{c)}	35,27	7,45 ^{d)}	27,85	,001***
Illuminance	1160,55 ^{a)}	3280,04	317,59 ^{b)}	608,40	322,18 ^{b)}	941,99	663,17 ^{c)}	1941,75	,001***
Temperature	18,21 ^{a)}	2,91	16,85 ^{b)}	2,46	16,80 ^{b)}	2,49	17,42 ^{c)}	2,61	,001***
Heating expenses	30,33 ^{a)}	96,21	71,67 ^{b)}	156,49	73,09 ^{b)}	160,95	50,31 ^{c)}	128,69	,001***
Hottest day									
Consumption	,00 ^{a)}	,00	2,65 ^{a)}	10,77	7,83 ^{a)}	20,91	,52 ^{b)}	3,68	,001***
Illuminance	1554,46	2628,09	486,52	728,97	432,91	751,95	889,47	1546,45	,549
Temperature	21,44 ^{a)}	2,16	18,84 ^{b)}	1,54	18,83 ^{b)}	1,49	19,93 ^{c)}	1,79	,001***
Heating expenses	,49	2,41	3,23	15,05	6,38	23,05	1,94	10,78	,217
Coldest day									
Consumption	9,09	32,61	17,65	40,90	19,17	41,46	11,42	35,45	,225
Illuminance	914,51	1616,64	347,41	653,95	253,96	461,14	522,11	949,02	,702
Temperature	15,76	3,55	15,49	3,72	15,48	3,71	15,65	3,60	,890
Heating expenses	146,17	234,82	244,25	334,23	242,01	332,92	198,45	285,61	,585

In terms of consumption, $F(3, 11174,339) = 150,037$, $p = ,001$, the multiple comparison tests indicate that group 2 is significantly lower in the group without blind. The Illuminance, $F(3, 11091,755) = 185,310$, $p = ,001$, tests revealed major statistical differences, being the lowest value in the group with blind, and the highest in the group without blind. The temperature $F(3, 10550,368) = 329,103$, $p = ,001$, was higher in the group without blind and lower in the group with blind and group 1. The heating expenses, $F(3, 11436,641) = 169,480$, $p = ,001$, comparison tests showed that these were lower in the group without blind and higher in the group with blind and group 1.

- Hottest day (interior window films)**

The consumption, $\chi^2_{KW}(3) = 17,832$, $p = ,001$, tests indicate that the statistically significant differences are between group 2 and the other groups. In terms of temperature, $\chi^2_{KW}(3) = 37,935$, $p = ,001$, the statistically significant differences occurred between the group without blind, the group with blind and group 1, as well as among group 1 and group 2.

- Coldest day (interior window films)**

The group differences in all variables were not statistically significant ($p > ,05$).

Tabel 2 – Daily average electricity consumption with lighting, illumination, indoor temperature and cooling expenses for the heating season with the application of exterior window films

	Without blind		With blind		Group 1		Group 2		Group 3		Sig
	M	Dp	M	Dp	M	Dp	M	Dp	M	Dp	
Heating season											
Consumption	5,12 ^{a)}	24,17	10,98 ^{b)}	32,60	15,28 ^{c)}	36,50	8,25 ^{d)}	28,89	5,75 ^{a)}	25,38	,001***
Illuminance	1160,55 ^{a)}	3280,04	317,59 ^{b)}	608,40	285,93 ^{b)}	827,27	547,90 ^{c)}	1555,19	923,15 ^{d)}	2611,26	,001***
Temperature	18,21 ^{a)}	2,91	16,85 ^{b)}	2,46	16,56 ^{c)}	2,58	16,98 ^{b)}	2,59	16,99 ^{b)}	2,60	,001***
Heating expenses	30,33 ^{a)}	96,21	71,67 ^{b)}	156,49	85,68 ^{c)}	179,96	62,51 ^{d)}	146,63	62,67 ^{d)}	147,17	,001***
Hottest day											
Consumption	,00	,00	2,65	10,77	9,57	23,33	,78	4,50	,00	,00	,021*
Illuminance	1554,46	2628,09	486,52	728,97	384,25	660,47	735,97	1239,49	1236,05	2089,98	,661
Temperature	21,44	2,16	18,84	1,54	18,60	1,52	19,38	1,66	19,41	1,68	,001***
Heating expenses	,49	2,41	3,23	15,05	15,44	41,05	2,87	13,96	2,92	14,28	,002**
Coldest day											
Consumption	9,09	32,61	17,65	40,90	20,75	42,55	12,23	36,41	9,71	33,98	,246
Illuminance	914,51	1616,64	347,41	653,95	225,47	405,32	431,47	760,20	726,81	1285,16	,805
Temperature	15,76	3,55	15,49	3,72	15,27	3,86	15,38	3,80	15,37	3,85	,842
Heating expenses	146,17	234,82	244,25	334,23	266,00	361,74	227,29	315,11	226,40	317,55	,627

The consumption, $F(4, 11974,892) = 130,442, p = ,001$, multiple comparison tests indicate that all the differences were statistically significant, being the lowest value in the group without blind and the highest one in group 1. In terms of illuminance, $F(4, 30,907) = 505,773, p = ,001$, its number was low in the group with blind and group 1, and higher in the group without blind. The temperature, $F(4, 11355,998) = 250,248, p = ,001$, tests revealed that group 1 is significantly different from the others, as well as the group without blind. The differences between the rest of the groups were not statistically significant. The heating expenses, $F(4, 12079,427) = 157,090, p = ,001$, were at its lowest in the group without store and highest in the group 1 and with blind.

- **Hottest day (exterior window films)**

In the matter of consumption, $\chi^2_{KW} (4) = 11,533, p = ,021$, the statistically significant differences were found between the group without blind and group 2. The temperature, $\chi^2_{KW} (4) = 34,743, p = ,001$, indicate that the differences were higher between the group without blind and the groups 1, 2 and with

blind. Groups 1 and 2 were also statistically different. Concerning the heat expenses, $\chi^2_{KW} (4) = 16,619, p = ,002$, the statistically significant difference was found between group 1 and 2.

- **Coldest day (exterior window films)**

The group differences in all variables were not statistically significant ($p > ,05$).

7.2 Cooling season analysis

The cooling season lasted from June 1st to September 30th.

Table 3 – Daily averages of electricity consumption (consumption), illuminance (illuminance), interior temperature (temperature) and cooling energy consumption (cooling expenses) for the cooling station with the application of interior window films

	Without blind		With blind		Group 1		Group 2		Sig.
	M	Dp	M	Dp	M	Dp	M	Dp	
Cooling season									
Consumption	,22 abc)	6,34	2,78 abc)	75,85	11,96 b)	385,44	,99 c)	30,97	,000**
Illuminance	6457,80	174878,27	1305,84	35338,47	1799,11	50286,49	3699,04	103290,38	,137
Temperature	26,33 a)	2,74	24,35 a)	2,03	24,42 c)	2,01	25,27 d)	2,24	,000***
Cooling expenses	502,09	13589,85	180,78	4893,49	178,79	4927,08	306,13	8343,53	,378
Hottest day									
Consumption	,00	,00	,43	2,08	5,49	16,22	,00	,00	,281
Illuminance	4105,89	9664,34	740,74	1134,20	1145,02	2755,61	2353,39	5665,89	,255
Temperature	26,52 a)	1,68	25,11 b)	1,25	25,18 c)	1,12	25,76 a)	1,29	,001***
Cooling expenses	462,92	622,77	216,65	287,56	209,16	277,33	308,80	405,73	,226
Coldest day									
Consumption	,00	,00	1,04	5,08	6,00	16,95	,00	,00	,201
Illuminance	1972,33	3277,00	448,64	524,12	548,85	936,55	1128,89	1929,27	,197
Temperature	23,52 a)	1,48	21,22 b)	1,76	21,28 a)	1,74	22,44 b)	1,81	,000***
Cooling expenses	61,11 a)	96,65	,00 b)	,00	,00 b)	,00	5,76 b)	21,00	,000***

The consumption, $F(3, 9666,065) = 6,218, p = ,010$, indicate that group 2 is significantly different from group 1. In terms of temperature, $F(3, 8223,633) = 6,218, p = ,010$, the comparison tests showed that the group without blind and group 2 were statistically different from the other groups.

- **Hottest day (interior window films)**

The temperature, $\chi^2_{KW}(3) = 25,327, p = ,001$, statistically differences were most significant between the group without blind and groups 2 and with blind, as it was the differences between group 1 and 2.

- **Coldest day (interior window films)**

The temperature, $\chi^2_{KW}(3) = 36,721, p = ,001$, multiple comparison tests indicate that, apart from the group without blind and group 2, all differences were statistically significant. Concerning the cooling expenses, $\chi^2_{KW}(3) = 17,694, p = ,001$, the comparison tests determined that the group without blind is statistically different from the rest of the groups.

Table 4 – Daily averages of electricity consumption (consumption), illuminance (illuminance), interior temperature (temperature) and cooling energy consumption (cooling expenses) for the cooling station with the application of exterior window films.

	Without blind		With blind		Group 1		Group 2		Group 3		Sig
	M	Dp	M	Dp	M	Dp	M	Dp	M	Dp	
Cooling season											
Consumption	,22 ab)	6,34	2,78 ab)	75,85	14,92 a)	442,61	1,29 b)	37,07	,36 ab)	10,37	,002*
Illuminance	6457,80	174878,27	1305,84	35338,47	1596,29	44217,58	3061,67	83261,59	5136,74	139103,80	,210
Temperature	26,33 a)	2,74	24,35 a)	2,03	24,16 a)	2,03	24,94 ab)	2,17	24,98 ac)	2,18	,000**
Cooling expenses	502,09	13589,85	180,78	4893,49	153,06	4319,02	266,80	7234,16	272,65	7380,00	,521
Hottest day											
Consumption	,00	,00	,43	2,08	7,14	18,41	,00	,00	,00	,00	,538
Illuminance	4105,89	9664,34	740,74	1134,20	1015,87	2422,52	1948,94	4567,35	3265,73	7687,83	,327
Temperature	26,52 a)	1,68	25,11 b)	1,25	25,03 b)	1,14	25,54 b)	1,20	25,57 ab)	1,20	,000***
Cooling expenses	462,92	622,77	216,65	287,56	190,09	258,02	282,63	370,80	289,14	382,87	,398
Coldest day											
Consumption	,00 ade)	,00	1,04 ade)	5,08	7,77 c)	19,19	,00 ade)	,00	,00 ade)	,00	,022*
Illuminance	1972,33	3277,00	448,64	524,12	487,02	822,16	933,79	1544,29	1568,96	2607,62	,257
Temperature	23,52 a)	1,48	21,22 b)	1,76	20,90 b)	1,77	21,99 b)	1,82	22,04 ab)	1,85	,001***
Cooling expenses	61,11 a)	96,65	,00b)	,00	,00 b)	,00	,00 b)	,00	,00 b)	,00	,005**

The consumption, $F(4, 11974,892) = 9659,394, p = ,002$, results indicate that group 1 is significantly different from group 2. Regarding temperature, $F(4, 8479,018) = 462,368, p = ,001$, the comparison tests indicate that, except groups 2 and 3, all differences were statistically significant.

- **Hottest day (exterior window films)**

The temperature, $\chi^2_{KW}(4) = 21,407, p = ,001$, differences were statistically significant between the group with blind and the groups

1,2 and without blind, and amongst group 1 and 2. **Coldest day (exterior window films)**

The consumption, $\chi^2_{KW}(4) = 11,429, p = ,022$, analysis indicates that group 1 was significantly different from groups 2, 3 and without blind. In matters of temperature, $\chi^2_{KW}(4) = 36,686, p = ,001$, the differences were mostly between the group without blind and groups 1, 2 and with blind. The cooling expenses, $\chi^2_{KW}(4) = 14,922, p = ,005$, significantly differences were found amongst the group without blind and groups 1 and 2.

8. Conclusions

This dissertation perceived the study of interior and exterior solar control window films in terms of energy efficiency in a building. The first stage of work consisted of analyzing the influence that the window films have on the optical parameters of each type of glass. It is understood that the application of interior and exterior window films can reduce the solar factor and the visible transmittance of glass, depending on the technical features of both film and glass.

Through the use of Windows and Optics programs it was possible to comprehend the displayed behavior of the ensemble.

The second part of this study covered the solar control window films simulation, through the analysis of the thermal and energetic performances of a room in actual working conditions. The EnergyPlus program was used to simulate and model the data out of four different situations.

The conclusions drawn in this thesis show the potential that solar control films have in decreasing the energy consumption of a building as well as in reaching thermal comfort in its interior, especially when it comes to buildings in rehabilitation situations.

References

- [1] IPCC (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.
- [2] Buildings & Climate Change: A Summary for Decision-Makers, UNEP's Sustainable Buildings & Climate Initiative. Disponível em WWW: <URL:<http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf>>
- [3] Directive 2010/31/UE of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings
- [4] Directive 2012/27/UE of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency
- [5] D.Faggembauu, M. Costa, M. Soria, A. Oliva. Numerical analysis of the thermal behavior of ventilated glazed facades in Mediterranean climates. Part I: development and validation of numerical model, *Solar Energy* 75 (2013) 217-228
- [6] Oral GK, Yener AK, Bayazic NT. Building envelope design with the objective to ensure thermal, visual and accoustic comfort conditions. *Building and Environment* 39 (2004) 281-287
- [7] INE (2014). *Estatísticas da Construção e habitação 2013*. Lisboa: INE
- [8] *Master Installer Reference Guide*. Madico University, Madico Safetyshield
- [9] *High Performance Window Film, Comfort without compromise, Solar Control & Energy Savings Collection*, (2014). Eastman Chemical Company ????????
- [11] *High Performance Window Film, Comfort Without compromise. Llumar*
- [12] Norma 15752-1
- [14] T. Babaei, H. Abdi, C. P. Lim, S. Nahavandi, A study and a directory of energy consumption data sets of buildings, *Energy and Buildings* (2015). Disponível em WWW: <URL:<http://dx.doi.org/10.1016/j.enbuild.2015.02.043>>
- [15] F.H. Mallick, Thermal comfort and building design in the tropical climates, *Energy and Buildings* 23 (1996) 161-167. Disponível em WWW: <URL:<http://www.sciencedirect.com/sci-hub.org/science/article/pii/S037877889500940X>>
- [16] J Khedari, N Yamtraipat, N Pratintong, J Hirunlabh, Thailand ventilation comfort chart, *Energy and Buildings* (2015). Disponível em WWW: <URL:https://www.researchgate.net/publication/222566037_Thailand_ventilation_comfort_chart._Energ_Build>
- [17] Y. Huang, Optimal building envelope design based on simulated performance: History, current status and new potentials, *Energy and Buildings* (2015). Disponível em WWW: <URL:<http://www.sciencedirect.com/science/article/pii/S0378778815302668>>

[18] Rodrigues, A. , Canha da Piedade, A. , Braga, A. M. , *Térmica de Edifícios*, Lisboa. Edições Orion, Lisboa (Março 2009)

[19] RCCTE, *Regulamento das Características de Comportamento Térmico dos Edifícios*, Decreto de Lei no 80, de 4 de Abril de 2006, Porto Editora, Porto, 2006

[300] Therm 6.3 / Window 6.3, NFRC Simulation Manual (2013) – Ernest Orlando Lawrence Berkeley National Laboratory, US Department of Energy, EUA.

[301] Window 5.0 User Manual, For Analysing Window Thermal Performance (2001) – Lawrence Berkeley National Laboratory, Environmental Energy Technologies Department.

[302] Saint Gobain Glass (SGG). Manual do vidro, Saint-Gobain Glass Portugal, Vidro Plano, S.A., 2008