Small-scale Field Study of Window Films' Impact on Daylight Availability under Clear Sky Conditions

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Abstract

Daylight illuminance levels and their spatial distribution are important design elements to achieve indoor visual comfort conditions and sustainability in buildings during the operation stage. While a proper daylighting scheme increases the efficiency of the building, the excessive use of glazed surfaces can contribute to thermal and visual discomfort, hence increasing the cooling demand and use of artificial lighting. Solar control film (SCF) is a self-adhesive thin film that can be applied on glazing systems of existing buildings for retrofitting purposes to modify thermal and optical properties of the glass substrate. This paper analyses experimentally the impact of single glazing with different SCFs on the indoor illuminance levels and respective distribution on horizontal work plane by comparing the measured absolute values and the useful daylight illuminance metric. Field experiments using a small scale model with the glazing oriented to the south, in Lisbon, were performed for a 6 mm clear glass and four different SCFs applied on the external surface of the glass, under clear sky conditions during summer and winter solstice at 9h00, 12h00, and 15h00. The results show that all SCFs reduced the indoor illuminance, which demonstrate their potential for glazing refurbishment when indoor visual discomfort occurs in buildings.

Keywords

Daylighting, glazing system, window films, visual comfort, scale-model

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1 INTRODUCTION

Daylighting has played an essential role in the history and evolution of architecture. While the lack of natural light is known to cause negative effects on human health and mood (Potočnik & Košir, 2019), an appropriate strategy between lighting design and building project can improve the visual comfort and indoor environmental quality and the energy efficiency through the optimisation of artificial lighting, cooling, and heating energy needs (Aghemo, Pellegrino & Lo Verso, 2008; Cruz, Pereira, Gomes & Kong, 2019). Klepeis et al. (2001) showed that people spent more than 85% of their time in enclosed buildings and that daylighting is a fundamental functioning resource to be taken into account in buildings.

Computer simulations and scale models are two different approaches that can be used to accurately tackle daylighting systems in buildings exposed to lighting conditions. Both approaches can be evaluated under real sun and sky conditions or under artificial sun and sky conditions (Aghemo, Pellegrino, & Lo Verso, 2008). Software-based approaches broadened conventional practices of how daylight modelling was being performed. In the early years, this type of analysis was very time-consuming, computationally demanding, and not easy to handle. Faced with the emergence of computational modelling based on the mastery of physics involved, but not yet fully experimentally tested, building designers initially showed some reservations in integrating into their practices tools that did not allow the use and modelling by hand of the real materials involved in the lighting study to the extent that scale models did (Aghemo, Pellegrino, & Lo Verso, 2008; Ayoub, 2020). Nowadays, with higher computer power and more advanced simulation tools through the evolution of specialised hardware and development of complex algorithms (Reinhart & Fitz, 2006; Ayoub, 2020), the use of computer modelling to predict illuminance levels in the early stages of the building design has gained attention from professionals in the building sector. Different methodologies and tools to predict daylight behaviour in indoor environments have emerged, supported by sophisticated light transport algorithms that allow more accurate results within acceptable timeframes and the possibility to optimise the design of simple or complex design façades in order to promote the visual comfort and the energy efficiency of the building.

The use of scale models is widely accepted as an adequate method for daylight assessment of indoor environments of buildings (Boccia & Zazzini, 2015). While this method allows the daylight performance to be predicted in the early stages of the design process or in pre-refurbishment interventions, scale models, particularly small-scale ones, tend to overestimate the illuminance values on horizontal and vertical planes when compared to full-size buildings (Kesten, Fiedler, Thumm, Löffler, & Eicker, 2010). Studies comparing illuminance performance on the horizontal plane, measured in smallscale models and fullsize buildings, demonstrate that small-scale models outperform the real scenario or building they represent, under overcast sky conditions, by 10-30% (Reed & Nowak, 1955; Kim, Boyer, & Degelman, 1985; Love & Navvab, 1991; Cannon-Brookes, 1994, 1997). According to Cannon-Brookes (1997), errors in the physical representation of the indoor environment and difficulties in accurately defining photometric properties of materials can justify this discrepancy, as well as other physical parameters such as maintenance and dirt in the building. As underlined by Boccia and Zazzini (2015), experimental tests performed under real sky conditions produce a more realistic representation of the daylight performance when compared with tests conducted under artificial sky using sky simulators. Moreover, Kesten (2010) highlights that model scale factor is a function of the daylighting design purpose, where greater scales within 1:10 to 1:1 are appropriate to accurately assess more critical or advanced daylighting devices and useful for detailed building façades and rooms. Due to the scarcity of available information on visual performance of Solar Control Films (SCFs), the present study uses a small-scale model approach to test various SCFs with different optical properties to assess their performance when applied in singlepane glass units.

This paper aims to increase the research on solar control films (SCFs) by studying the indoor illuminance performance of office rooms with singlepane glass units without (reference scenario) and with 4 different solar control films (SCFs) – spectrally selective and reflective – for retrofitting purposes of existing buildings. This approach can be useful for refurbishment purposes in buildings with single-glazed windows in Mediterranean climates, Csa and Csb Köppen-Geiger climate classification (Rodrigues, Santos, Gomes, & Duarte, 2019), as is the case for Portugal, to increase visual comfort without having to activate shading devices or other solutions that can compromise the view to the outside (Silva, Gomes, & Rodrigues, 2015; Gomes, Rodrigues, & Bogas, 2012). In this study, illuminance levels were measured in a small-scale model 1:10 on a horizontal plane at 0.8 m (at full scale) under real sky conditions during summer and winter solstice for 5 different scenarios of the fenestration system. An analysis and discussion based on the registered absolute illuminance values and the useful daylight illuminance was performed and SCFs that presented the most suitable illuminance values to perform office activities (e.g. writing, typing, reading, data processing) were identified.

2 SOLAR CONTROL FILMS

Solar control film (SFC) is a thin laminate film material that can be applied to glass surfaces to alter their optical and thermal properties without having to change the type or structure of glazing systems in buildings façades (Pereira, Gomes, Rodrigues & Almeida, 2019). Nowadays, there is a high range of window films for retrofitting purposes with applications on both internal and external surfaces in glazed areas of buildings façades, appropriate for retrofitting purposes in cold and hot climates (Teixeira, Gomes, Rodrigues, & Pereira, 2020). Their efficiency is directly related to the glass substrate, solar orientation, external and internal shading conditions, airconditioning system, and local climate. Films that are applied on the external face of the glass surface present a lower durability than those applied internally due to the fact that they are exposed to weather elements and to possible damages induced by people or objects for glazing surfaces at the ground level. Also, inappropriate cleaning tasks or insufficient maintenance routines have proven to decrease the life span of the films (Pereira, Teixeira, Gomes & Rodrigues, 2019).

2.1 CONTEXT

The first window films were developed in the 1960s and had the main purpose of balancing heat exchanges through glass surfaces by blocking radiation across the entire range of frequencies of the electromagnetic spectrum (European Window Film Association, 2020). Although this was a major discovery with high potential to improve thermal and visual comfort in buildings, problems regarding the decrease of the external visibility (reductions in the visible light range spectrum), excessive increase of the use of artificial light and of the heating loads motivated new research and product development.

In the 1970s with the industrial revolution at its peak, new solutions and materials that improved comfort and energy efficiency in buildings were being investigated and developed. The incorporation of polyester fibres in window films produced more energy efficient films for cold climates due to the increase of the absorption coefficient and by re-irradiating long wave in the infrared electromagnetic spectrum and therefore reducing the heat losses to the outdoor environment without decreasing the visible solar transmittance through the glass surface.

Research and development of thin film materials is increasing. New innovative and more sustainable window films such as spectrally selective, adaptive, or smart films will increase their market share in future years.

2.2 TYPICAL CONSTITUTION

Existing window films are composed of several membranes of different materials intercalated with each other that can reach up to 8 different layers and undergo 7 different manufacturing procedures (European Window Film Association, 2020). Fig. 1 shows a standard structure of a solar control film.

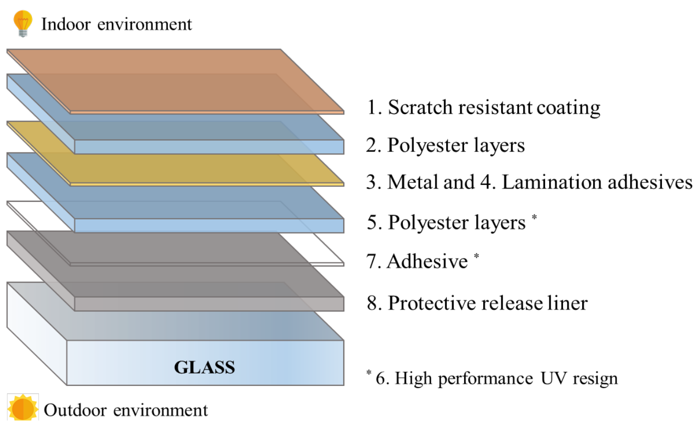


FIG. 1 Standard structure of a solar control window film with internal application on the glass surface: 1. scratch resistant coating, 2. and 5. polyester layers, 3. lamination adhesive(s), 4. metal, 6. high performance UV resin, 7. adhesive and, 8. protective release liner

As shown in Fig. 1, a typical layout of a solar control film with internal application on the glass surface can be constituted of eight different layers (European Window Film Association, 2020), namely:

- **1.** Scratch resistant coating: this hard acrylic-coated finishing layer is in contact with the indoor environment of the building and its function is to protect the film from scratching and abrasion.
- **2. and 5.** Polyester: the polyester membrane offers good optical, thermal, mechanical, physical and chemical characteristics to the film. It is very durable, resistant, and flexible and withstands high and low temperatures. It can have different types of finish, such as UV resin or adhesives. The incorporation of several layers of polyester (multi-layered structure), connected through lamination adhesives, increases the absorption and solar (front) reflectance coefficients. Many films are made with metal deposits on their polyester substrate. This type of film is in the range of solar control series due to the high solar (front) reflectance coefficient and are traditionally called reflective or metallised films.

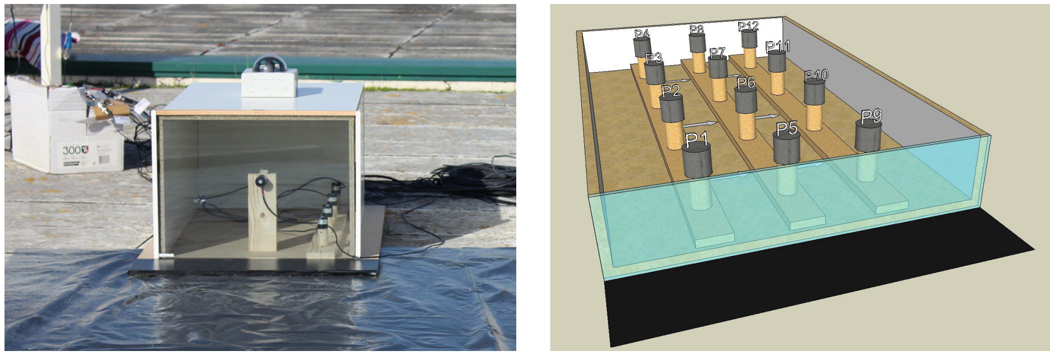
- **3.** Metal: the oxide metals presented in the solar control films are incorporated into the polyester membrane and have the function of reducing solar gains through glazing. The metal used is usually aluminium and can reduce solar gains by about 80% and reduce visible radiation between 15% to 70%. Recent films based on nanotechnology are produced without metal oxides, resulting in thin films with combined high visible transmittance coefficients and low solar (front) reflectance coefficients.
- **4.** Lamination adhesive: joins several layers of polyester through lamination processes. Sometimes they are embedded in the polyester membranes themselves.
- **6.** High performance UV resin: blocks UV radiation and protects the polyester layers and lamination adhesives. It can be incorporated in the adhesives or in the polyester layer itself. This resin improves thermal performance by reducing the solar gains in the UV solar spectrum and protects the indoor environment content from early degradation by exposure to UV rays.
- **7.** Adhesive: there are two types of adhesives in window films - pressure sensitive and water activated adhesives. The first one adheres to the glass surface through the application of pressure forces without the need to apply any type of solvent, water, or heat. On the contrary, water activated adhesives, as the name implies, needs water to ensure correct adherence, forming chemical bonds with the glass surface which guarantees a higher durability and a more transparent appearance, though its removal or replacement can be difficult.
- **8.** Protective release liner: a film usually made of polyester that protects the adhesive from contamination before installation. It should only be removed before applying the film to the glass.

3 EXPERIMENTAL ANALYSIS

3.1 EXPERIMENTAL SET-UP

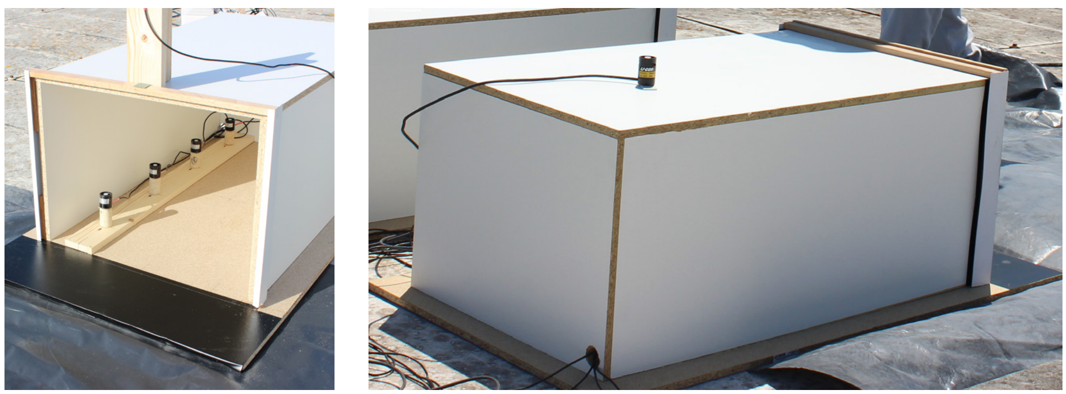
To evaluate the daylight illuminance levels and the spatial distribution of different solar control films (SCFs) applied in singlepane glass, *insitu* measurements of indoor illuminances on a horizontal plane were carried out in a small scale model (1:10) on the rooftop of DECivil building in Instituto Superior Técnico in Lisbon, Portugal. Taking advantage of the modularity of the model, five different glazing systems were tested: a singlepane clear glass of 6 mm, taken as the reference scenario, and four solar control films applied on the external surface of a 6 mm single-pane glass (designated as SCF A, SCF B, SCF C and SCF D). Tests were conducted with the glazing system of the scale model oriented south in the summer and winter solstice under clear sky conditions at three periods of the day 09h00, 12h00 and 15h00 (True Solar Time – TST).

Fig. 2a shows the small-scale model used in this study. The model was built 30 cm high, 40 cm wide and 70 cm long (internal measurements) in compliance with the daylighting rule of thumb where the depth of the daylight area of an indoor environment is between 1 to 2 times the size of the window-head-height (Reinhart, 2005) combined with the typical geometrical representation of office rooms in buildings. The surfaces were constructed using medium density fibreboards (MDF) and, except for the floor, all surfaces have white melaminic finishing. During the construction of the model, special attention was given to possible openings in the structure that could allow radiation to enter other than from the fenestration system and therefore interfere with the results. For this reason, silicone sealant was applied in some parts of the model as a precaution. In addition, to enable a swift exchange between different glass substrates and minimise the time interval between successive measurements, the model fenestration wall was designed to be completely filled with glass, without any other parts that could make glass assembly difficult. For the tests, the model was placed over black plastic to decrease the influence of the solar reflection from the ground and to protect the materials from the floor's humidity.



a b

FIG. 2 [a] Small scale model (1:10) on the rooftop of DECivil building in IST, Lisbon, Portugal, and [b] position of the indoor luxmeter sensors (12 points)



a b

FIG. 3 [a] Indoor, and [b] outdoor luxmeter sensors on horizontal plane

Illuminance values were measured with luxmeter LI-COR LI200 sensors (± 5% accuracy) across a grid of 12 points (Fig. 2b) on a horizontal plane at 0.08 m (0.8 m at full scale) above the floor, corresponding to the common height of the work plane. In the small-scale model, a wooden ruler with 4 luxmeter sensors fixed on stoppers (Fig. 2b and Fig. 3a) was placed in three different positions (right, central, and left) during the measurements. The right, central, and left illuminance points were measured at different moments in time, taking about 2 minutes to record all the 12 illuminance values on the horizontal plane for each glass substrate. This timeline was tested on the rooftop in one pilot day previously to the first real measurement during the summer solstice in order to test the facility and understand the logistics of the tasks involved. Details regarding the timelines and steps of each measurement were registered and a total of 8 minutes was the time observed to place, measure, and withdraw each glass substrate, resulting in a total of 40 minutes in each of the three periods of the day (09h00, 12h00, and 15h00, TST).

As a result, all the measurements were established to start 20 minutes before and end about 20 minutes after the schedule time (09h00, 12h00, and 15h00, TST), with the following sequence being adopted: 1° SCF A, 2° SCF B, 3° SCF C, 4° SCF D, 5° clear glass. Outdoor illuminance on the horizontal plane was measured at one point in the model's exterior (Fig. 3b) at each of the three periods of the day. Additionally, photos were captured inside the model for all the 5 tested fenestration systems.

3.2 GLAZING SOLUTIONS

In this study, the indoor illuminance values and distribution on a horizontal plane at 0.08 m (0.8 m at full scale) above the floor was assessed for five glazing solutions: singlepane clear glass unit with 6 mm (reference glazing) and four SCFs applied on the external surface of the reference glass. Table 1 shows the main thermal and optical properties of the analysed solutions. These properties were obtained using Window and Optics tools (Curcija, Vidanovic, Hart, Jonsson, & Mitchell, 2018) which allow spectral data of combined layers of glass with applied films to be calculated. While SCFs *A* and *B* are spectrally-selective films and can be identified by their high visible transmittance (*SCF A*: τ_{vis}= 39%; *SCF B*: τ_{vis}= 66%; *SCF C*: τ_{vis}= 16%; *SCF D*: τ_{vis}= 35%), SCFs *C* and *D* are reflective films and show higher values of solar (front) reflectance (*SCF A*: $\rho_{f,sol}$= 25%; *SCF B*: $\rho_{f,sol}$= 27%; *SCF C*: ρ*f,sol*= 58%; *SCF D*: $\rho_{f,sol}$= 37%).

TABLE 1 Thermal and optical characteristics of the 5 different glazing solutions: solar transmittance, τ_{sol}, solar (front), $\rho_{f,sol}$, and (back), $\rho_{b,sol}$, reflectance, absorptance, α, visible transmittance, τ_{vis}, visible (front), $\rho_{f,vis}$, and (back), $\rho_{b,vis}$, reflectance, thermal transmittance, U, and solar factor, g

	τ_{sol} [%]	$\rho_{f,sol}$ [%]	$\rho_{b,sol}$ [%]	α [%]	τ_{vis} [%]	$\rho_{f,vis}$ [%]	$\rho_{b,vis}$ [%]	U [W/m².K]	g [%]
Clear glass	85	8	8	8	90	8	8	5.73	88
SCF A	22	25	13	52	39	7	12	5.62	44
SCF B	35	27	14	36	66	12	14	5.62	51
SCF C	11	58	55	30	16	58	58	5.63	23
SCF D	25	37	38	36	35	33	37	5.63	41

3.3 ILLUMINANCE EVALUATION METHODS

The daylight performance was evaluated through the absolute values of indoor illuminance on the horizontal plane considering 500 lx as the recommended value for comfortable daylighting illumination for office activities (e.g. writing, typing, reading, data processing) according to EN 12464-1 (2014) and considering the illuminance range values defined in the Useful Daylight Illuminance (UDI) metric (Nabil & Mardaljevic, 2005). Results of the absolute values of indoor illuminance for the 4 SCFs were analysed and compared with those obtained for the reference glazing. Nabil & Mardaljevic (2005), developed a new concept to assess daylighting in buildings through the UDI metric.
The UDI considers that values below 100 lx are insufficient and can contribute to an increase in the energy needs with artificial lighting, values between 100-300 lx require supplementary artificial lighting, and values above 3000 lx can cause thermal and/or visual discomfort and therefore values in these illuminance ranges are not considered useful. On the contrary, values between 300 lx and 3000 lx are considered useful and desirable for indoor environments.

4 RESULTS AND DISCUSSION

The analysis was carried out under clear sky conditions in the summer (21st June) and winter (21st December) solstice when the sun's elevation angle is at its highest and lowest, respectively, with respect to the annual solar dynamic behaviour. For both days, indoor and outdoor horizontal (h=0.8 m) illuminance values were measured at 3 different hours: 09h00 (solar radiation from the east), 12h00 (solar radiation from the south), and 15h00 (solar radiation from the west). The 12 individual data points with experimental measured illuminance values for each tested fenestration system were interpolated and extrapolated for mapping the illuminance distribution along the entire horizontal work plane area.

4.1 ANALYSIS OF THE DAYLIGHT AVAILABILITY BY THE ABSOLUTE ILLUMINANCE VALUES

Fig. 4 to Fig. 9 comprise the digital photos showing the indoor illuminance values on the horizontal plane at 0.8 m height at full scale (work plane) in a scale ranging from 0 to >10 klx at 9h00, 12h00, and 15h00 under clear sky conditions in both summer and winter solstices, for the 5 scenarios of the fenestration system: Clear glass; SCF A; SCF B; SCF C and; SCF D. The photos were taken from the interior of the small-scale model with a Canon EOS 600D camera, controlled remotely. The outdoor illuminance on horizontal plane, *E_out*, registered at 09h00, 12h00, and 15h00 in the summer solstice was of 72 klx, 104 klx, 116 klx, and in the winter solstice of 29 klx, 59 klx and 36 klx.

During both summer and winter seasons, all SCFs significantly reduced the indoor illuminance values, presenting in the summer solstice lower illuminance values than the ones obtained in the winter solstice. This can be explained by the higher summer sun angles and thus lower values of incident direct radiation on a south-oriented façade in the summer period when compared to the winter period (Roos, Polato, van Nijnatten, Hutchins, Olive, & Anderson, 2001). This phenomenon is also noticed in the photos captured inside the small-scale model (see Fig. 4 and Fig. 7, as examples).

At the summer solstice, illuminance values on a horizontal plane for the glass with SCFs vary between 0-1000 lx in a significant area of the horizontal working plane at 0.8 m, except for *SCF B* which is the film with the higher value of the solar transmittance. While the *clear glass* and *SCF B* showed values higher than 500-1000 lx on almost all of the total area of the work plane, SCFs *A*, *C*, and *D* showed illuminance values between 500-1000 lx on more than 50%, which results in a better visual performance by preventing possible glare situations. The *clear glass* and *SCF C* scenarios showed the highest and the lowest range of illuminance values, varying between 0.33-10 klx and 0.34-2.11 klx, respectively, which results in a higher and lower daylight availability asymmetry throughout the horizontal working plane.

In the winter solstice, as expected, the illuminance values were higher for the *clear glass* since it is the fenestration scenario with the highest solar factor, presenting illuminance values higher than 500 lx and on all of the horizontal working plane area, and above 10 klx on 50% of the horizontal working plane area. The *clear glass* scenario's results indicate that visual discomfort through the influence of glare situations can occur, making this space unpleasant or even impossible to work on without the activation of complementary shading devices. SCFs *A*, *B*, and *D* also showed values well above the recommended values of 500 lx to perform office tasks while the reflective *SCF C* showed illuminance values closer to the ones recommended during the morning and afternoon periods (09h00 and 15h00).

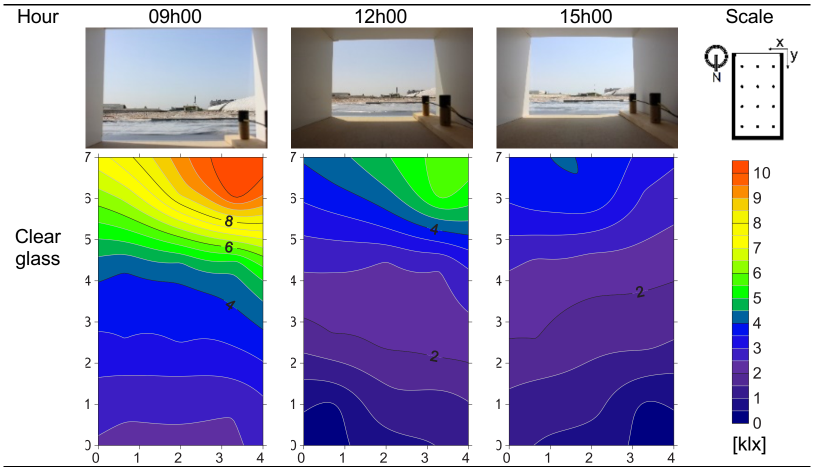


FIG. 4 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the clear glass (E_out^09h00=72klx; E_out^12h00=104klx; E_out^15h00=116klx)

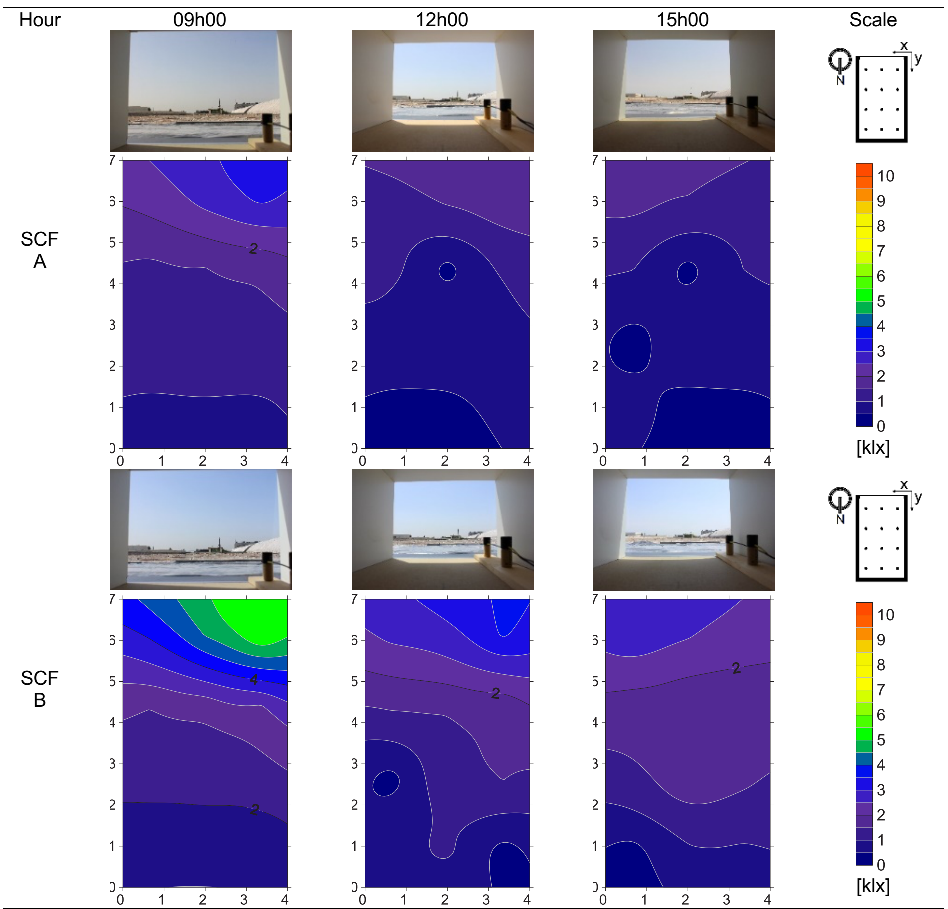


FIG. 5 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the spectrally-selective films A and B (E_out^09h00=72klx; E_out^12h00=104klx; E_out^15h00=116klx)

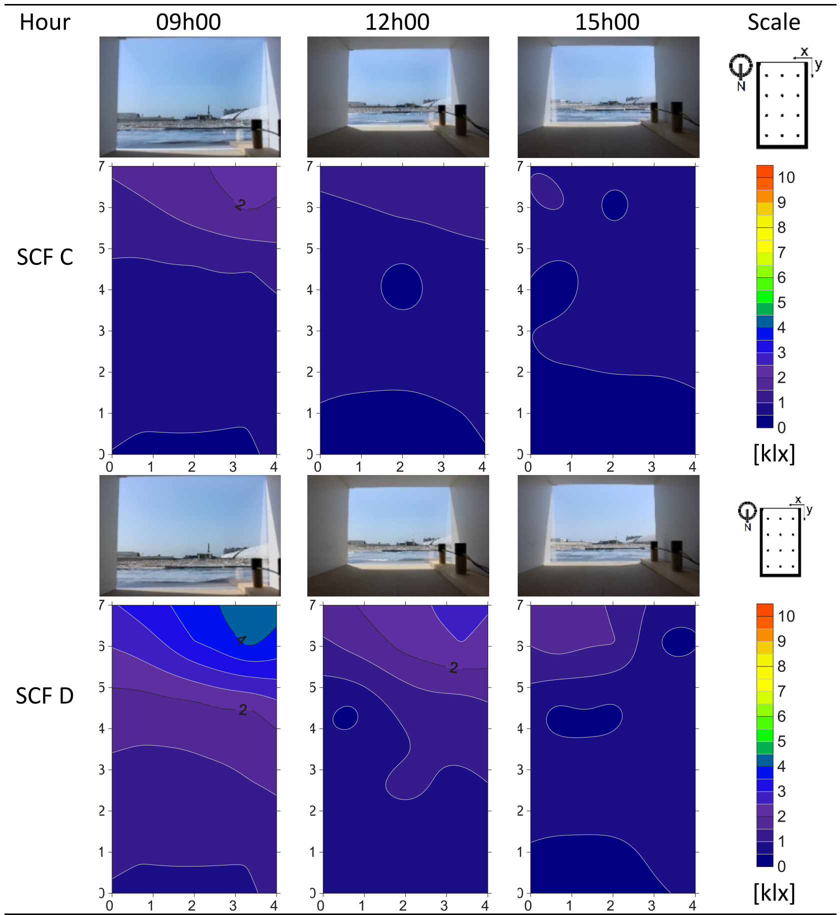


FIG. 6 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the reflective films C and D (E_out^09h00=72klx; E_out^12h00=104klx; E_out^15h00=116klx)

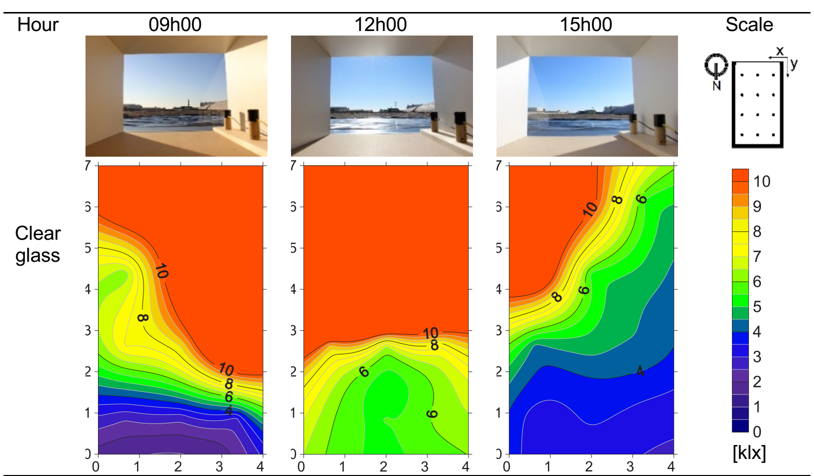


FIG. 7 Digital photos and indoor illuminance levels on a horizontal plane at 09h00, 12h00 and 15h00 at the winter solstice under clear sky conditions for the clear glass (E_out^09h00=29klx; E_out^12h00=59klx; E_out^15h00=36klx)

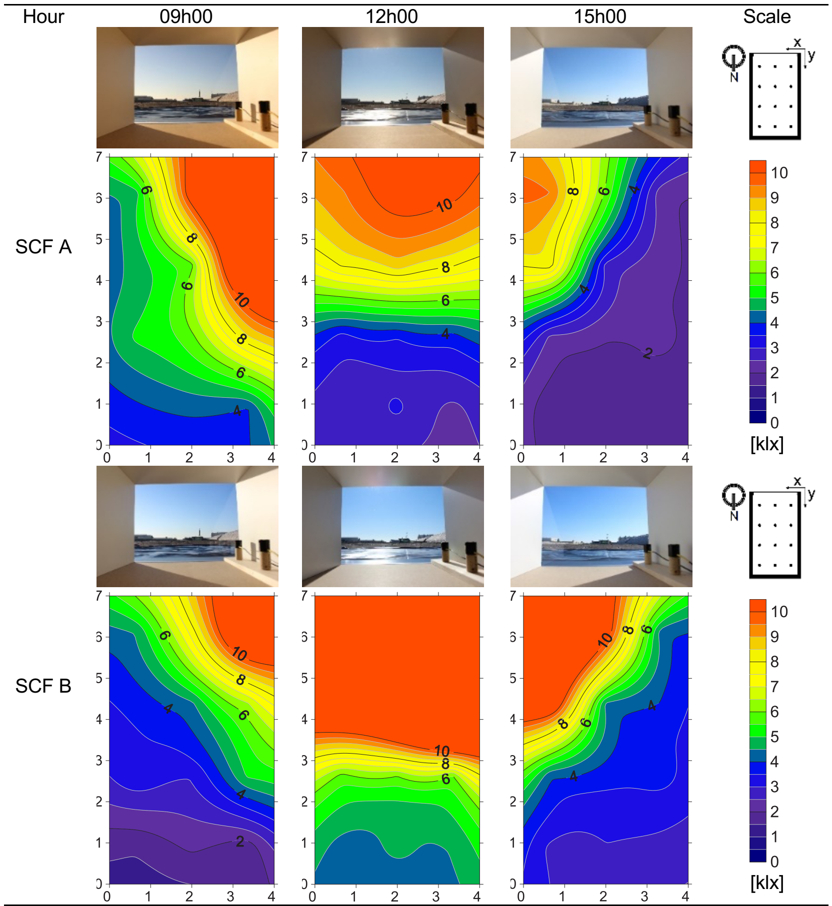


FIG. 8 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the winter solstice under clear sky conditions for the spectrally-selective films A and B (E_out^09h00=29klx; E_out^12h00=59klx; E_out^15h00=36klx)

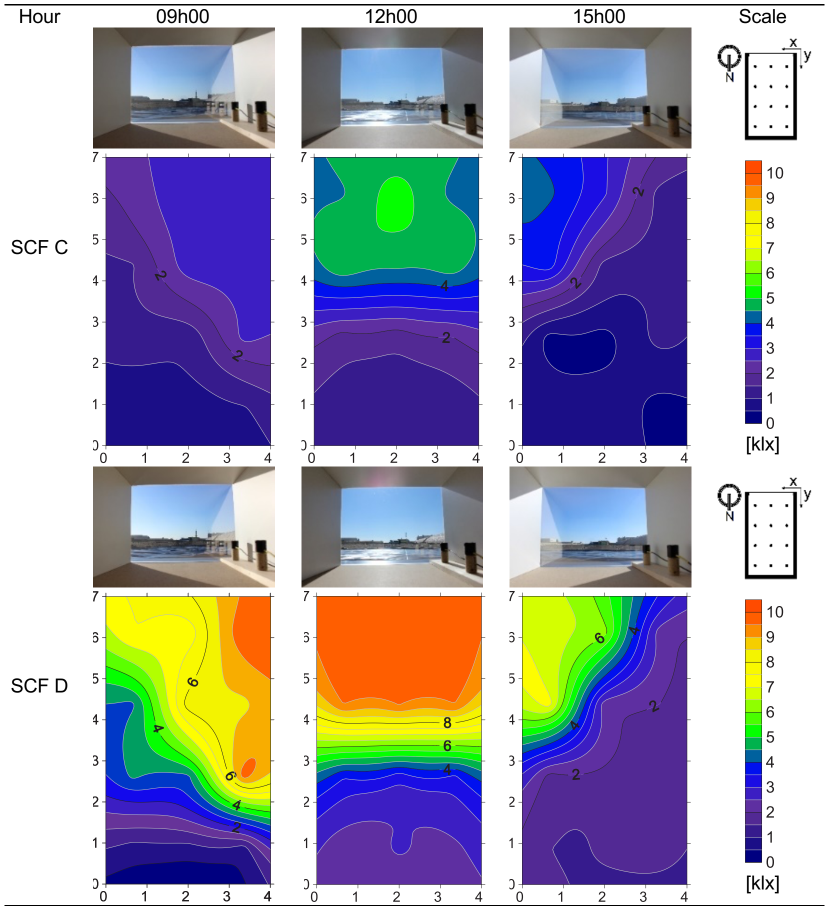


FIG. 9 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the winter solstice under clear sky conditions for the reflective films C and D (E_out^09h00=29klx; E_out^12h00=59klx; E_out^15h00=36klx)

4.2 ANALYSIS OF THE DAYLIGHT AVAILABILITY USING THE USEFUL DAYLIGHT ILLUMINANCE RANGE VALUES

Fig.10 to Fig.15 show the digital photos and indoor illuminance values at an adequate scale to analyse the areas within the range values (<100 lx insufficient, 100-300 lx supplementary artificial lighting required, 300-3000 lx useful, >3000 lx can cause thermal and visual discomfort) considered in the Useful Daylight Illuminance (UDI) metric for three hours of the day at the summer and winter solstices, respectively, under clear sky conditions for the 5 scenarios of the fenestration system: Clear glass; SCF A; SCF B; SCF C and; SCF D.

Analysing the experimental results at the summer solstice through the range values defined in the UDI metric, it is possible to conclude that the reference scenario, *Clear glass*, showed the highest area of illuminance values outside the useful range (>3 klx) which indicates that this scenario presents a high risk of causing visual discomfort conditions to perform any type of work activity. In the summer solstice, SCFs *A* and *B* showed a high area of the work plane within the useful illuminance range value, however on the winter solstice almost all the illuminance values are above the useful range. The most reflective film, *SCF C*, presented values within the useful range throughout the day on the entire area of the work plane except during the winter solstice at 12h00. *SCF D* showed medium values between the 2 spectrally selective SCFs *A* and *B*.

At the winter solstice, the results of the reference scenario, *clear glass*, presented illuminance values outside the useful range in almost all the working plane area, which indicates that from 09h00 to 15h00 the illuminance levels are so high that visual discomfort associated with glare is very likely to occur. Spectrally selective SCFs *A* and *B* showed, during the morning and afternoon periods, small areas within the useful range of illuminance values (0.3-3 klx) in the working plane area. The reflective SCFs *C* and *D* presented a higher area of the grid within the useful illuminance values, especially *SCF C* with more than 50% of the grid area within the useful values during the morning and afternoon periods. In fact, when compared to the other films, *SCF C* (τ_{sol}= 11%, τ_{vis}= 16%) provides the highest decrease of the illuminance values and thus is the most appropriate retrofitting scenario to prevent possible glare situations during both summer and winter seasons.

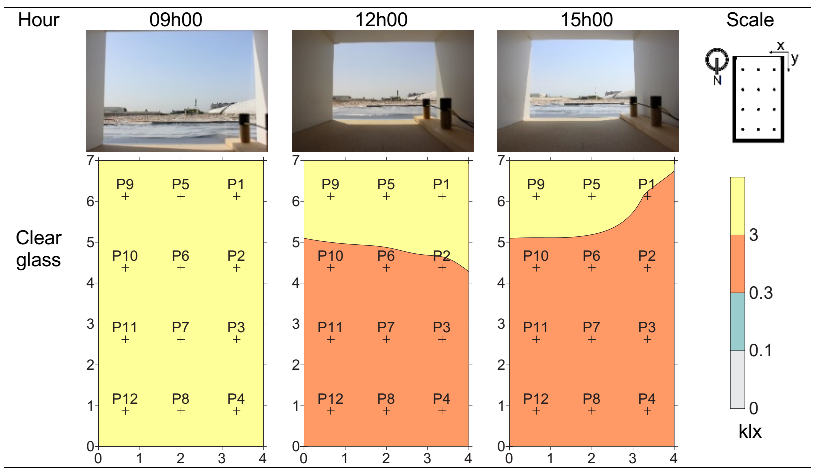


FIG. 10 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the clear glass using the UDI's range values (E_out^09h00=72klx; E_out^12h00=104klx; E_out^15h00=116klx)

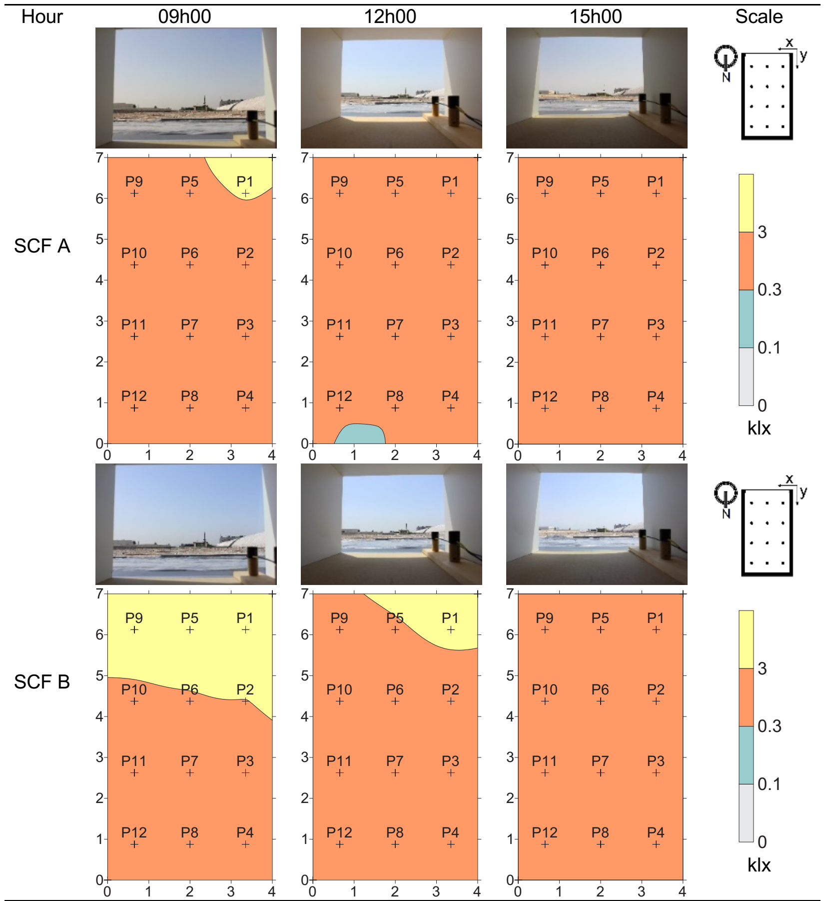


FIG. 11 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the spectrally-selective films A and B using the UDI's range values (E_ out^09h00=72klx; E_out^12h00=104klx; E_out^15h00=116klx)

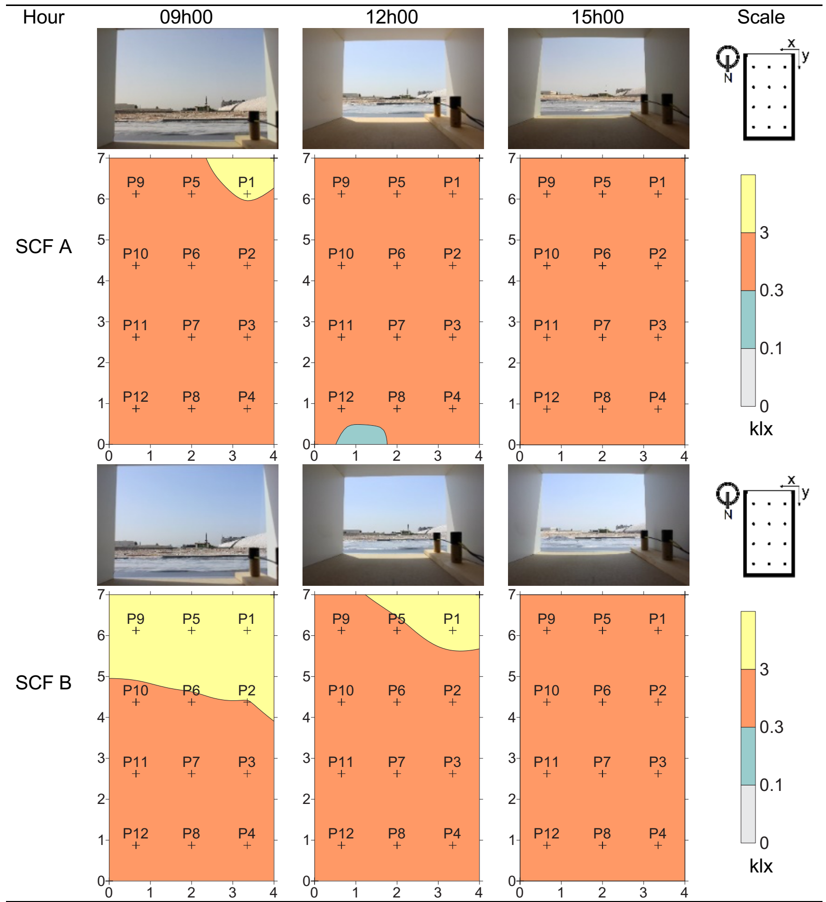


FIG. 12 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the summer solstice under clear sky conditions for the reflective films C and D using the UDI's range values (E_{out}^{09h00}=72klx; E_{out}^{12h00}=104klx; E_{out}^{15h00}=116klx)

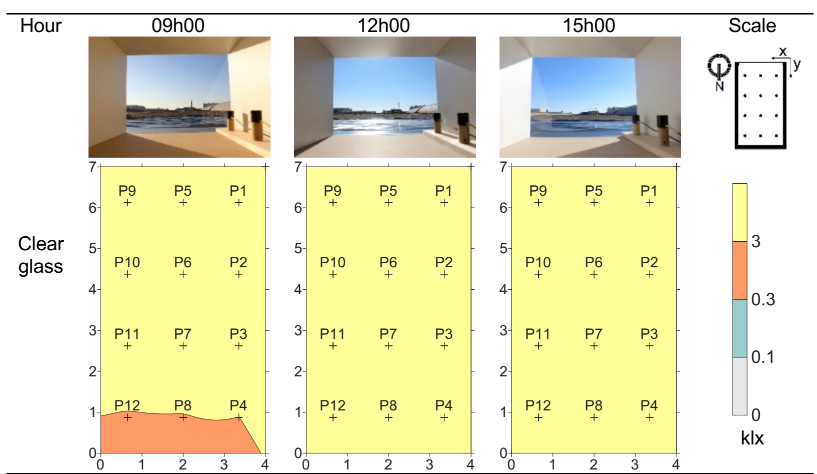


FIG. 13 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the winter solstice under clear sky conditions for the clear glass using the UDI's range values (E_{out}^{09h00}=29klx; E_{out}^{12h00}=59klx; E_{out}^{15h00}=36klx)

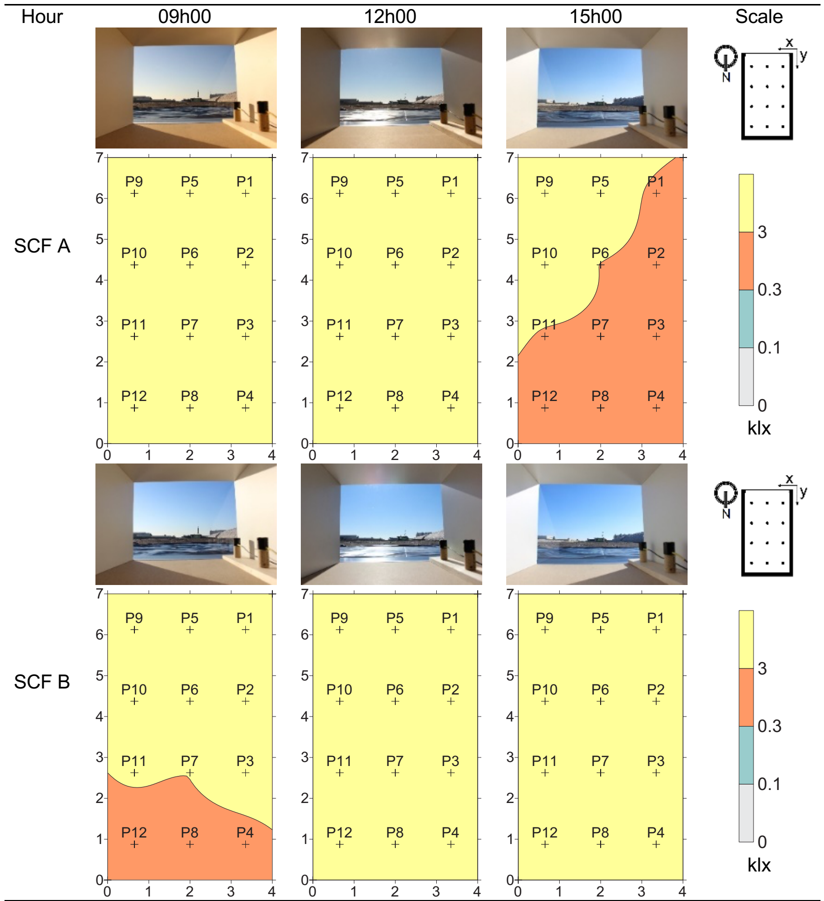


FIG. 14 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the winter solstice under clear sky conditions for the spectrally-selective films A and B using the UDI's range values (E_{out}^{09h00}=29klx; E_{out}^{12h00}=59klx; E_{out}^{15h00}=36klx)

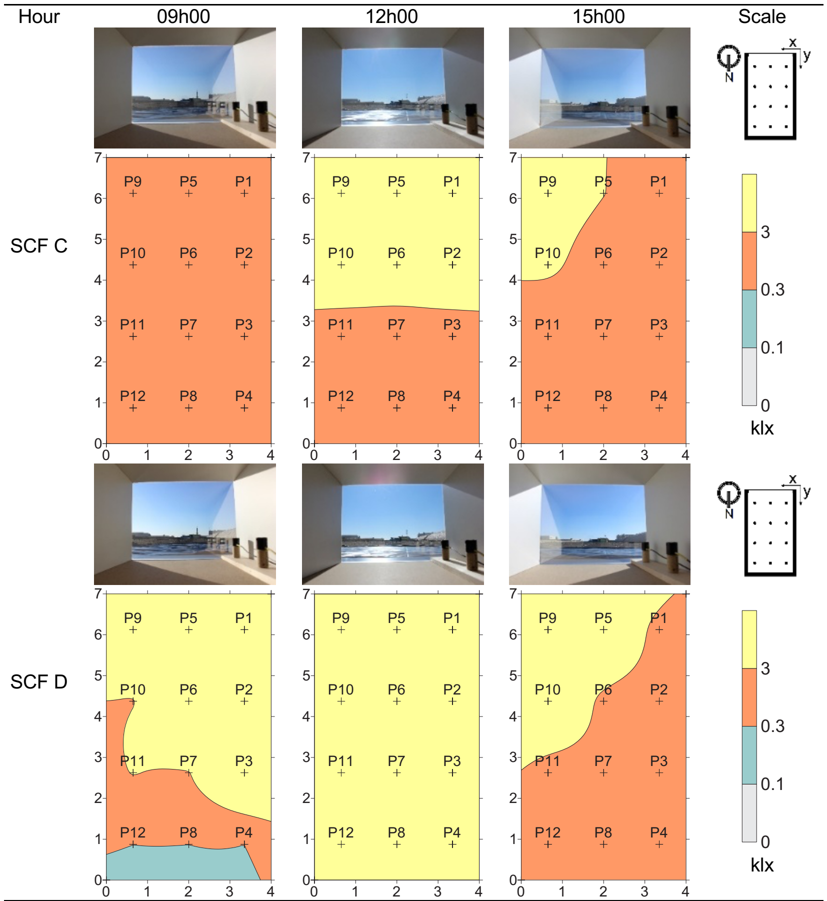


FIG. 15 Digital photos and indoor illuminance levels on a horizontal plane at 0.8 m height at 09h00, 12h00, and 15h00 at the winter solstice under clear sky conditions for the reflective films C and D using the UDI's range values (E_out^09h00=29klx; E_out^12h00=59klx; E_out^15h00=36klx)

5 CONCLUSIONS

This study shows the potential of highly reflective and spectrally selective solar control films in promoting daylight availability and limiting visual discomfort in office rooms with singlepane clear glass windows, in Mediterranean climates with predominantly clear sky conditions, by decreasing the solar gains and visible transmittance through the glazing system. The several intercalated layers of polyester with incorporated metal oxides and high-performance UV resin in the films' composition provide the thermal and optical properties that make these films a potential viable solution for the refurbishment of glazing systems. Usually, SCFs are applied on windows to improve the thermal performance of existing buildings by decreasing either the solar factor, when the aim is to prevent excessive solar gains, or the surface emissivity of the glazing, when the goal is to increase the thermal insulation of the windows (Pereira et al., 2019; Teixeira et al., 2020). For South European countries, as is the case for Portugal, window films are mainly applied to control solar gains, thereby preventing overheating and decreasing the cooling energy needs. The application of a window film may increase the thermal comfort conditions and the energy efficiency of the building, but the impact in the daylight availability due to the decrease of the visible transmittance of the glazing may be a problem that has not yet been sufficiently investigated (Cruz et al., 2019).

In this study, the indoor illuminance distribution on the horizontal work plane at 0.8 m was measured under clear sky conditions at the summer and winter solstice using a small-scale model for 5 different glazing systems. A single pane of 6 mm clear glass was tested and taken as the reference scenario. Furthermore, four different solar control films, two spectrally selective and two reflective, were applied to the external surface of a 6 mm single-pane clear glass and tested.

The results show that for single-pane glass systems, SCFs can significantly decrease the indoor daylight illuminance levels likely to cause glare problems (≥ 3 klx), which is a relevant issue in locations with predominantly clear sky conditions. The application of SCF in glazing showed a greater performance in summer, when compared with single glazing without SCF, not only in decreasing the illuminance levels below the critical values (3 klx), but also in promoting a more extensive spatial distribution of acceptable levels of daylight availability (0.33 klx). In winter, the performance of these films was not as noticeable as in summer, due to the sun's lower height and greater perpendicularity of the sun's rays to the glazing surface.

The application of the spectrally selective SCFs *A* and *B* and reflective SCFs *C* and *D* on a 6 mm single pane of glass decreased the illuminance indoor values throughout the work plane, which had a positive effect in lessening possible glare situations due to the high illuminance levels, in both summer and winter seasons.

The highly reflective film, SCF C, which has the lowest solar and visible transmittance, was found to be the best retrofitting scenario in providing illuminance values within the useful range (0.3-3 klx) according to the UDI metric ranges in clear sky days. Therefore, this film has the highest potential to increase the visual comfort conditions in office rooms with single pane clear glass oriented to the south, showing illuminance values closer to 0.5 lx in a higher area of the work plane and preventing possible glare situations when compared to the other films, during sunny days in both summer and winter seasons. In fact, except SCF C, for which the area with acceptable values of illuminance during the winter is considerable, the other three SCFs lead to a higher risk of glare occurrences in the whole room extension. During the winter solstice when compared to the summer solstice under clear sky conditions, SCF C showed higher illuminance values across the working plane. On the one hand, this film decreased the daylight availability reducing the risk of glare occurrences during both summer and winter seasons, and on the other hand, as the results showed, it did not decrease the daylight values to a point where supplementary artificial lighting is required for office work activities. Nevertheless, to overcome the problem with glare occurrences, movable shading devices might be considered as a feasible complementary solution, especially during the winter period under clear sky conditions.

This paper focused the analysis only on visual comfort and under clear sky conditions, which are typical of southern European countries, where summer is the dominant season. Window films, when compared to shading solutions, decrease the solar and visible transmittance of glazing systems without compromising the view to the outside, which, alongside the ease of maintenance (same as the glass without SCF) and flexibility in application, is an advantage. As a possible drawback of the films studied, that may cause suspicion in the use of window films, the lower durability of this solution is pointed out when compared to traditional ones. Depending on the type of application (on the internal or external side of the glass), the service life of these films can vary from 6 to 12 years and thus requires frequent replacements to maintain the same performance throughout the building operation stage, which can be a disadvantage of SCFs when compared to shading solutions. Another potential drawback is the decrease of the daylight availability and the heat gains during the winter season, which can lead to higher energy demand with electric lighting and heating loads.

Therefore, although these films proved to be appropriate, when the aim is to minimise the risk of visual discomfort, it is recommended in the design to extend the analysis to overcast sky conditions and to thermal comfort, even if these are not the prevailing climate conditions in southern European countries such as Portugal.

The results of this study show that SCFs are highly influential on the indoor illuminance levels and therefore the studies on visual comfort metrics and on thermal and energy efficiency indicators should not be considered separately but instead in an integrated approach that enables a better understanding of the trade-offs between the variation of solar and visible transmittance and the heat gain/losses coefficients derived from the application of the film. Additionally, a combined approach between SCFs and other shading devices should be considered to increase the visual comfort conditions when higher illuminance levels are registered.

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