DOI: https://doi.org/10.1016/j.energy.2021.121083

Energy, environmental and economic analysis of windows' retrofit with solar control films: a case study in Mediterranean climate

Júlia Pereira[a*], Cristina Camacho Rivero[b], M. Glória Gomes[a], A. Moret Rodrigues[a], Madelyn Marrero[b]

[a] CERIS, Department of Civil Engineering, Architecture and Georesources (DECivil), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

[b] Higher Technical School of Building Engineering, Department of Architectural Constructions II, University of Seville, 41012 Seville, Spain

Abstract

The incorporation or the replacement of materials in buildings may decrease the energy use during the operational stage but increase the embodied energy in a building's life cycle. In this study, three different solar control films (SCFs A, B and C) with application on the existing windows of a building are investigated through an energy, environmental and economic perspective over a defined life cycle period. The full replacement of the existing window with a new one is also analyzed as an alternative retrofitting solution. Retrofitting solutions with higher light-to-solar gain ratios showed higher energy savings during the use stage by decreasing the solar gains in a higher proportion than the decrease of the visible transmittance. The best retrofitting solution, SCF C, showed a life cycle energy (LCE) (embodied plus operational energy) and a carbon footprint of 4447 $MJ/m^2/40y$ and 380 $kgCO_2eq/m^2/40y$, respectively, whereas the least performant solution, new window, showed a LCE 1.5 times higher than the average of the three SCFs. The higher LCE value of the new window was found to be related to the higher value of the embodied energy when compared to that of the three SCFs (~9 times higher than the average of the films).

Keywords

Life cycle assessment; Building retrofitting; Glazing system; Solar control films; Embodied and operational energy; Carbon footprint.

***Corresponding author:** Júlia Pereira, phone: +35121841857, e-mail: julia.pereira@tecnico.ulisboa.pt

1. Introduction

Operational energy typically accounts for 80% of life cycle energy of a building and the majority of a building's life cycle GHG emissions [1], allowing for significant energy and cost saving potential. In fact, energy saving and efficiency of energy use, as an intrinsic part of any country's sustainable development, should not be only focused on the building's service life, but a more comprehensive approach is required: the entire life cycle of the construction. As a result, not only the operational energy (OE) shall be accounted for but also the embodied energy (EE), which is the total energy required for the extraction, processing, manufacturing and delivery of buildings [2]–[4].

Both OE and EE are an outcome of the Life Cycle Assessment (LCA) approach, which is widely recognized as the reference method for estimating the overall environmental performance throughout the life cycle of a building, from cradle to grave [5], [6]. This global approach that considers both energy consumptions to assess the energy efficiency of a building is particularly justified by the better thermal insulation of a building. In a recent study [7], insulation materials have proven to improve the EE of buildings, demonstrating that EE plays a significant share in the LCA of energy efficient buildings. A study developed by Seo et al. [8] verified that when pre 2005 dwelling stocks are upgraded to meet current minimum requirements for new houses in Australia, the heating and cooling energy can be reduced up to 76%, but the EE needed for this upgrade is ~50% of the energy consumption. Having looked at different retrofitting options, the authors also concluded that double glazing units and wall insulation materials were the retrofitting solutions that showed higher values of EE. In fact, with the advent of energy efficient building systems and appliances, operational energy of buildings has seen a remarkable reduction, which makes embodied energy and carbon emissions increasingly significant in the building's life cycle and thereby an aspect of growing importance to be considered in the design, construction, and operation of sustainable buildings.

Studies regarding the operational and the embodied energy of buildings through the use of the LCA approach can be found in the literature (e.g. [9]–[12]). Praseeda et al. [9] showed that the share of operational and embodied energy depends on the type of materials used in construction and on the extent of space conditioning adopted. In a review study, Vilches et al. [13] concluded, in turn, that the relationship between the materials' embodied energy (*EE*) and the operational energy (*OE*) changes from 20%(*EE*) vs. 80%(*OE*) to 40%(*EE*) vs. 60%(*OE*), due to refurbishment and renovations practices. These results show that retrofitting measures for reducing energy consumption in buildings may increase the EE and, therefore, for a more complete and accurate estimation of the overall energy performance and environmental impact of a building during its life cycle, both energy components shall be accounted for.

Windows are the weakest components of the building enclosure by increasing the heat losses in winter and the solar gains in summer and the impact is proportional to the area they occupy in façades [14]–[16]. For these reasons, windows are within the first building elements which demand attention as regards the implementation of energy retrofitting measures. Thermal and visual comfort problems are more acute in office buildings since the proportion of glazing areas found in façades is greater than in the opaque areas.

In this paper two retrofitting solutions for the glazing areas of an office building are analyzed using the LCA methodology. One alternative is the traditional solution of replacing the existing glazing by a more energy efficient window from the visible light and solar heat gain standpoint. A comprehensive study involving film coatings in open-plan office buildings in subtropical climate [17], [18] showed that the use of coatings in glazing coupled with daylight-linked lighting control systems increased the lighting and cooling energy savings in ~28%. The influence of embodied energy and carbon emissions in the LCA assessment of glazing systems has been investigated in several studies including different transparent façade systems [19]–[21], coatings and inert gasses [22], and frames [23]–[25]. The competing alternative of replacing the existing window is the application of a solar control film (SCF) to obtain modified solar and visible optical properties that reduce energy consumption while improving people's comfort. SCFs are thin laminates with specific optical properties that are applied to the glass after manufacture or installation to alter their properties either by the method of reflection or absorption [26]. In the literature, there are examples of related studies that indicate that the use of SCFs can save energy and thus enhance the energy performance of the buildings. On this topic, [27]–[31] concluded that the use of SCFs can result in an annual decrease of energy consumption since they reduce both the shading coefficient and the solar heat gain as well as the summer cooling load. A study of an office building in a Mediterranean climate with single pane windows and a south facing façade showed an annual decrease of energy consumption of up to 68.2% [31]. Another study on the daylight and energy assessment of window films in double-pane windows with a south-west solar orientation [32] reported a decrease of incoming solar radiation up to 60% and a decrease of indoor air temperature, in sunny days, of ~2-3ºC. Recent studies [33], [34] concluded that while reflective films can provide higher thermal and visual comfort in office rooms, spectrally selective films provide higher annual energy performance by decreasing the cooling loads in a higher proportion than the increase of the heating loads and electric lighting and can substantially reduce the environmental impacts related with CO_2 emissions.

To the knowledge of the authors, no previous study has analyzed the use of SCFs on glass as a retrofit solution for energy efficient windows based on a complete LCA model, considering both EE and OE, and involving an economic evaluation in an integrated approach.

The purpose of the present study is to assess the energy, environmental and economic differences of three different SCFs as retrofitting solutions for the glazing areas of an existing building located in Lisbon and to enhance its energy efficiency over a defined life cycle period. For comparison purposes, the full replacement of the existing windows for new ones was also investigated. Based on experimental data collected *in-situ*, a building energy simulation was modelled, and the operational energy was assessed for the different scenarios of the window. A life cycle analysis study of the embodied (*EE*) and operational (*OE*) energy of the building required to ensure thermal and visual comfort was then performed for the two alternative retrofitting scenarios considered – application of SCF or replacement with new windows –, and the obtained results discussed. Also, an economic and environmental analysis was performed to assess the investment costs and the greenhouse gas emissions associated with the retrofitting scenarios. Such an approach can be useful to support the management of office buildings that present low thermal and/or visual comfort conditions and high glazing areas in the façades which can be observed in temperate Mediterranean climates.

2. Materials and methods

2.1 Goal and scope of the LCA study

Regarding energy rehabilitation of buildings-related projects, the decision-making process on alternative strategies is essentially based on the operational energy savings that can be achieved and the economic costs involved. Although other factors such as the environmental sustainability and the life cycle of products are particularly important in decision-making today, their effective consideration has been far from desirable. In this context, it is expected that the LCA model can give a useful input in the decision-making process since it gives numerous life cycle outcomes of a product, consequence of human activities, with potential impact on the environment and therefore can be used for product comparison over the whole life cycle period.

The systems examined in the LCA process comprise the products and processes included in the life cycle of the following three scenarios: *Sc1*) original window; *Sc2*) retrofitting of the existing window using a solar control film (SCF) for three films (SCFs A, B and C); *Sc3*) retrofitting through full replacement with a new window (NW). *Sc1* is considered the base case scenario – no intervention is done to the building – and *Sc2 and Sc3* the two alternative retrofitting scenarios. Operational and embodied energy, as well as the carbon footprint, are the LCA outcomes used in this study for comparative evaluation and supporting decision-making in retrofitting options of the building glazed area. Further, a more holistic overview of the system performance, considers the economic costs incurred in the life cycle of the three SCFs as well as the NW, which represent another performance measure and provide more comparison information upon the different solutions for the building glazing area.

2.2 Databases and calculation tools

The LCA study was carried out using the SimaPro Life Cycle Assessment tool, which is a well-recognized sustainability software package with which complex life cycles can be modelled and analyzed according to the ISO 14040 principles [35]. At the core of the LCA process is the life cycle inventory (LCI). To build the LCI dataset regarding the materials and activities involved in the retrofitting works the Ecoinvent database [36] was employed.

In this study, the bill of quantities and works information of the construction project, essential to perform the corresponding LCI, were not available whereas in the case of the glazing retrofitting scenarios they did not exist at all. Measuring the layout elements concerned and using the Andalusia Construction Cost Database (ACCD) to obtain items of work and schedule of quantities that allow compiling the final inventory were a way of bypassing the problem [37]. The applicability of this Spanish database ACCD to Portuguese buildings has been previously verified using the Carbon Footprint indicator [38].

Complementary to the tools used specifically for the LCA approach, the popular building energy simulation program EnergyPlus [39] is employed in this work to predict the OE use based on the required heating, cooling and artificial lighting demand to maintain indoor thermal and visual comfort. An experimental campaign was also performed in one office area where parameters such as the indoor and outdoor temperatures, global and diffuse solar radiation were measured and used to verify the predictions of the building simulation model. The reliability of these predictions greatly depends upon the quality and consistency of the data provided by the EnergyPlus. This includes the data on the solar and visible optical properties of glazing systems, which implies the availability of credible and constantly updated databases and tools able to handle this information and perform the calculations. Window and Optics [40] are software packages widely accepted in the fenestration industry to determine performance indices and optical properties of complex glazing systems. This makes these software programs appropriate to generate baseline data of optical properties and for this reason they can be applied to measure the existing and retrofitting solutions of the glazed area of the building.

2.3 Life cycle period of window retrofit

Since this study involves a comparison between three scenarios - existing window (*Sc1*), different SCFs (*Sc2*) and a new window (*Sc3*) - using the LCA methodology for its evaluation, the life cycle period is considered to start when retrofitting takes place. Given that the useful life of windows is established around 30-50 years [23], to enable a comparable timeline between SCFs and NW, a life cycle period of 40 years was considered. As the useful life of the

SCFs selected for this study is estimated around 10 years [41], and given the building life cycle of 40 years, the film will be installed three times after the first retrofitting.

Since retrofitting is a process that occurs after the building has been completed, the life cycle stages of the LCA methodology do not involve the building itself but only encompass the new competing construction solutions, with the building being regarded as a previously finished and consolidated system. Thus, the following stages are the focus of the present work: *Product stage*, associated with raw material supply, transport and manufacturing only referring to the retrofitting construction products; *Construction stage*, associated with transport to workplace and installation construction process only of the retrofitting products, and *Use stage*, related with the impacts during the life-cycle only of the implemented retrofitting solutions. Finally, the *End-of-Life* stage, which includes the disposal, recycle and reuse stages, was not considered particularly interesting because the destiny of most products after use is uncertain, as such it was not included in the study.

The life cycle of the proposed study is shown schematically in Figure 1. As *Sc1* is related to the original glazing, no major intervention is required besides normal maintenance during the life cycle period in this scenario.

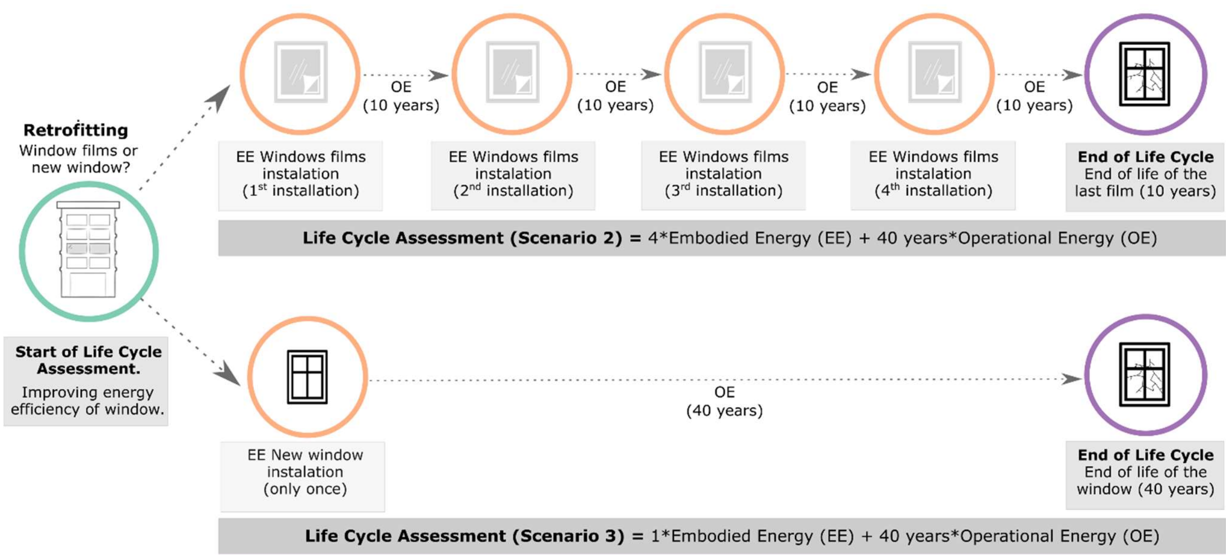


Figure 1. Timeline of events in the life cycle period for retrofitting scenarios *Sc2* and *Sc3*

2.4 Organization of the work

The methodology proposed in this work is organized into two scales of approach - a room scale (a), adopted to collect experimental data used to verify an energy simulation model representative of the building of the case study, and a building scale (b), adopted for investigating the life cycle performance of the fenestration solutions under study.

The methodology provided in Figure 2 comprises the following steps:

a. experimental campaign in a representative office room in the existing conditions, i.e. with the original window prior to any retrofitting intervention with SCF, to verify a building energy simulation model using the use of EnergyPlus and Sketchup programs;

b. definition of the three analysed case scenarios: *Sc1*) original glazing of the base case study; *Sc2*) original window for three alternative SCF solutions applied on the external surface of the glazing; and *Sc3*) replacement of the original window by one alternative new window;

c. building energy simulation (BES) based on the EnergyPlus, SketchUp, Window and Optics programs to assess the building operational energy (*OE*) of the three analysed scenarios;

d. embodied energy (*EE*), carbon footprint (*CF*) and economic costs (*EC*) assessment of the building for the three analysed case scenarios through the LCA approach; in correspondence with the type of element installed in the fenestration area - NW or SCF - the bill of quantities can be prepared from the work units concerned, taken from the Andalusia Construction Cost Database, and surface area that fenestration occupies in the building envelope; with the total amount of resources consumed (materials consumption in the retrofitting solutions) and the Ecoinvent database [36] implemented in the SimaPro software, it is possible to obtain the energy and greenhouse gas emissions involved in the production (materials extraction, transport and manufacture) of the retrofitting elements and determine the environmental indicators: Embodied Energy (*EE*) and Carbon Footprint (*CF*). Likewise, the good execution of the budget associated with materials and construction works, from data provided by ACCD, and the operational energy costs provided by PORDATA [42], allows to perform the economic evaluation of the analysed scenarios.

e. finally, a comparison of the operational energy, environmental impacts and economic costs of the base case and the retrofitting strategies for the glazing area of the façade is carried out.

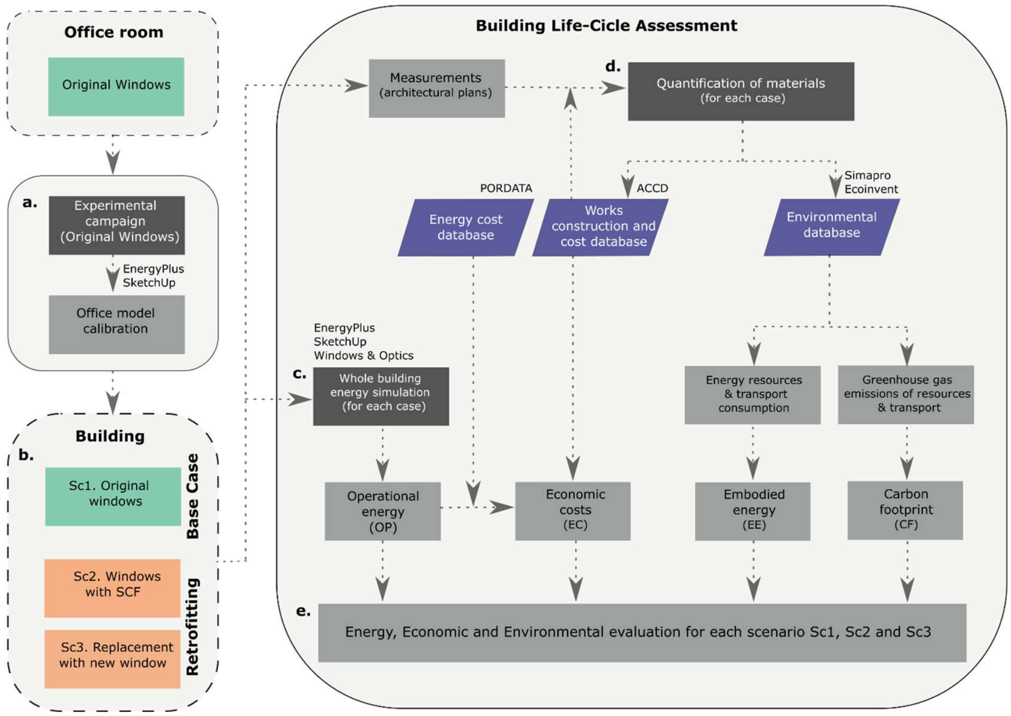


Figure 2. Methodology flowchart

3. LCA calculation process

3.1 Operational energy

Building energy modelling has become a preferred method to predict energy demand and evaluate different retrofitting scenarios based on energy performance and other metrics in recent years [43]. In this study, the operational energy (*OE*) is considered in the LCA approach as the primary energy required to maintain the thermal and visual comfort in the case study building and was assessed through a whole building energy simulation (BES) using both the EnergyPlus and the SketchUp 3D modelling software over the defined 40 years life cycle. Window and Optics simulation tools were used to model the thermal and optical properties of the different windows retrofitting scenarios [40]. BES models allow to predict the energy use under the influence of external inputs (e.g. weather, occupancy and infiltration) to maintain specified performance criteria, such as, indoor temperature and humidity.

Firstly, one typical office area – representative of the office areas of a building – with a south facing façade was verified using data collected from an experimental procedure conducted during the heating and cooling seasons. The accuracy of the model was assessed by two standardized statistical indexes - the Normalized Mean Bias Error, N_{MBE}, and the Coefficient of variation of the Root-Mean Square Error, $C_{v,RMSE}$ [44]. The verification of one typical office area allows for a better modelling representation of the indoor spaces that are under study. Another consideration is that it allows to tune and adjust the properties of the materials of the surroundings and have a closer agreement between experimental and simulated indoor temperatures within the office areas. Secondly, a building energy simulation (BES) model was dimensioned in the SketchUp and EnergyPlus software by using the complete architectural plans, detailed construction descriptions, and the materials' properties tuned through the verification process for the office areas in the building.

The annual *OE* of the building was calculated as shown below (1):

$$OE = \left(\frac{EN_{heat}}{COP} + \frac{EN_{cool}}{EER} + EN_{light}\right) \times P_{EF} \quad (1)$$

where

EN_{heat} = energy needs with heating

EN_{cool} = energy needs with cooling

EN_{light},= energy needs with lighting

These indicators were obtained from BES for the three alternative scenarios of the glazing. The efficiency ratios of the HVAC equipment considered in the equation are: the coefficient of performance (*COP)* and the energy efficiency ratio (*EER*) used to convert the energy needs into energy use and the primary energy factor of electricity generation, P_{EF}, used to convert energy use into primary energy.

It must be noted that the *OE* considered in the calculations, only accounts for the share of the building energy charged to the windows, to be coherent with the embodied energy calculation, which relates solely to the window systems. The *COP* and *EER* used to convert the energy needs into energy use were 3.0 and 3.4 [45], respectively, and a primary energy factor, P_{EF}, of 2.5 kWh_{EP}/kWh [45] was considered.

3.2 Embodied energy and carbon footprint

To estimate the embodied energy and the economic and environmental impacts related to the glazing retrofitting operations, it is necessary to quantify all the resources involved in the *Product stage* (raw material extraction, transport to factory and manufacture of retrofitting products), the *Construction stage* (transport to site, assembly and installation of retrofitting products), and in the maintenance operations (concerned to retrofitting products) during the *Use stage* and make the subsequent conversion into energy and carbon emissions by multiplying the resource quantities by proper coefficients representing the energy consumed and the CO_2 equivalent per resource unit (kg, liters, m^2, m^3) [46].

To obtain the consumed resources of the retrofitting works for the different analyzed scenarios, a methodology that incorporates an internal economic and environmental cost database, based on ACCD, was employed in the analyzed case study [47], [48]. This cost database uses a classification system organized hierarchically whereby each group is divided into subgroups of similar characteristics [37]. The unitary costs representing the group of materials, necessary to complete a unit of traditional construction work (work unit) are included at the lower level of the hierarchic structure. Once the work units corresponding to the envisaged retrofit solutions are identified in the database and the involved glazing areas are measured, it is possible to quantify the resources broken down into materials, manpower and machinery. For the inventory, associated with the retrofitting systems, only materials are accounted for computing *EE* and *CF* of the building life cycle.

To obtain both the *EE* and the *CF* of a particular product or building component, firstly, the mass of the constitutive materials (kg) is obtained. Then, the Cumulative Energy Demand (CED) and the International Panel of Climate Change 100a (IPCC 100a) impact indicators are applied not only to respectively estimate the primary energy use to calculate the *EE* but also to measure the total GHG emissions expressed in CO_2 equivalent to calculate the *CF*, per kg of manufactured material. The environmental database used in both indicators, is Ecoinvent, implemented in SimaPro and developed by the Swiss Center for Life cycle Inventories, due to its transparency in the development of processes, consistency, references, and the outstanding fact that it fuses information from several international databases of the construction industry.

The procedure which is applied in the retrofit of a building window for each scenario formerly analysed is shown in the following equations:

$$EE_M = \sum_i M_i \times \left(E_{mat_i} + E_{trans_i}\right) \quad (2)$$

$$CF_M = \sum_i M_i \times \left(I_{mat_i} + I_{trans_i}\right) \quad (3)$$

where

EE_M and CF_M = embodied energy and CO_2 equivalent associated with the material resources involved in the retrofitting alternatives.

M = mass of a basic constitutive material of the retrofitting work.

E_{mat} and E_{trans} = primary energy consumption of manufacture and transport of the material.

I_{mat} and I_{trans} = CO_2 equivalent of manufacture and transport of the material.

The life cycle energy (LCE) for each retrofitting solution, throughout the 40 years life-cycle is given by the following formula extended to the number of retrofitted windows:

$$LCE = \sum_i EE_{M_i} + OE \tag{4}$$

where

EE_M (equation 2) = embodied energy during the *Product* and *Construction* stages.

OE (equation 1) = operational energy during the *Use stage*.

On the other hand, the carbon footprint, *CF*, associated with all the retrofit windows for each scenario throughout the 40 years life-cycle is shown below:

$$CF = \sum_i CF_{M_i} + I_{OE} \times \frac{OE}{P_{EF}} \tag{5}$$

where

CF_M (equation 3) = *CF* during the *Product* and *Construction* stages and the CO_2 equivalent associated with the energy use during the *Use stage*.

I_{OE} = conversion factor from electricity to carbon emissions in Portugal (0.28271 $kgCO_2eq/kWh$ [49]).

The environmental and economic impacts associated with the maintenance and cleaning operations were assessed by using data from [46], by built surface (11.42 m^2), as provided in Table 1.

Table 1. Economic (*EC*) and environmental costs (*EE,* embodied energy and *CF*, carbon footprint, respectively), for the maintenance and cleaning operations during the life cycle [46]

Item	*EC* [€/m²/y]	EC_{TOTAL} [€/m²/40y]	*EE* [MJ/m²/y]	EE_{TOTAL} [MJ/m²/40y]	*CF* [$kgCO_2eq/m^2/y$]	CF_{TOTAL} [$kgCO_2eq/m^2/40y$]
Cleaning	42.2300	19 294.04	0.916	418 416.10	0.259	118 286.23
Maintenance	0.0104	4 755.06	4.563	2 084 756.20	1.290	589360.58

3.3 Economic costs

The economic costs, *EC*, associated with the different retrofitting solutions of the glazing system were determined for all the window area of the building of the case study and for a 40 years life-cycle period according to the following equation (6):

$$EC = EC_{ini} + \sum_{k=1}^{k=\frac{N}{R}-1} \frac{EC_{ini} \times (1+a')^{k\times R}}{(1+a)^{k\times R}} + \sum_{k=0}^{k=N-1} \frac{C_e \times OE \times (1+a')^k}{(1+a)^k} \tag{6}$$

where

EC = economic cost associated with each retrofitting solution.

EC_{ini} = initial cost with production and construction works of the retrofitting solution.

C_e = current value of the electricity cost for domestic consumers.

α' = harmonized index of consumer prices.

α = discount rate based on a 10year government treasury yield.

N = life cycle period (N=40)

R = periodicity of the retrofitting scenario (R=10 in *Sc2* and R=40 in *Sc3*).

The first sum represents the net present value of economic costs with product and construction works of the retrofitting solution during its life cycle, the second sum represents the net present value of economic costs with the annual operational energy imputed to the glazing systems (*OE*). Through the LCA methodology used in this study, the initial costs, EC_{ini}, associated with the retrofitting works, cleaning and maintenance tasks were calculated considering the bill of quantities and the work specifications taken from the ACCD. For the calculation of the net present value of periodic and periodic fixed annual costs that occur in different periods of time, the harmonized index of consumer prices obtained through the macroeconomic projections for the euro area by the European Central Bank [50], α', as well as the discount rate based on a 10 year government treasury yield [51], α, were considered. Regarding the electricity cost for domestic consumers, C_e, the current value of 0.215 €/kWh was assumed [42].

4. Case study

4.1 Description of the case study

The building considered in this study is in the south area of Lisbon, in Portugal, in front of the Tagus river (Figure 3). The city experiences a temperate Mediterranean climate (Köppen-Geiger: Csa/Csb) [52], [53] with an average annual temperature of 16ºC and minimum and maximum temperatures occurring from December to February, and from July to September, respectively.

Figure 3. External view of the building considered in this work and internal view of a typical office room

The building has a total floor area of 17 400 m^2 and glazing area of 1 732 m^2, approximately, and is divided into three main areas: an area consisting of halls, security rooms and a conference room and two areas of office spaces, one with south-north oriented façades and three floors and the other with east-west oriented façades and four floors.

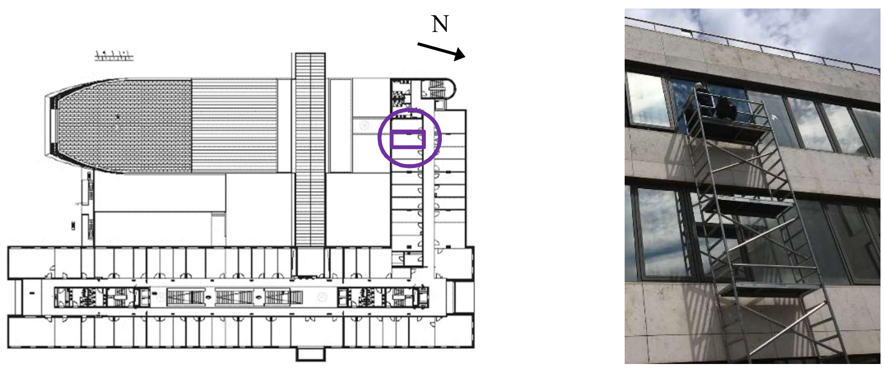
Exterior walls are double brick (11 + 11 cm) with an air gap of 7 cm partially filled with extruded polystyrene (4 cm) and floor slabs are in reinforced concrete (20 cm). The original windows have argon filled double glazed units with a 14mm argon chamber (from the outer to the inner panes of the glass: 8mm low-ε glass, 14mm argon, 8+8mm laminated glass with a polyvinyl butyral coating) and due to thermal discomfort associated with overheating in the office spaces, a SCF was applied on the external surface of the outer pane in all the glass area of the façade. The SCF, which was applied before this study, with the purpose of decreasing the solar gains through the windows without compromising the view, reached their end of life and revealed several problems regarding its integrity as shown in Figure 4. As a result, the properties of the film were seriously affected, losing homogeneity throughout the glass area, and showing differences from window to window depending on the type of problem and the level of deterioration of the film. Therefore, the present study addresses the retrofitting solutions for the glazed area of the building considered in this study using the LCA methodology.

Figure 4. Examples of windows of the building considered in this study with the damaged SCF

4.2 Simulation modelling

To assess the *OE* of the building, first one typical south oriented office area located on the 2nd floor (Figure 5a) was selected to be monitored and the experimental data was used to verify an energy simulation model of the typical office areas of the building. The experimental campaign was performed during the periods from 15th of August to the 14th of September in the summer and from 1st to the 31st of January in the winter. Indoor and outdoor temperatures and outdoor irradiance on vertical and horizontal plane were monitored continuously using T-type thermocouples and LI-COR LI200R pyranometers connected to two data loggers Delta T DL2, one located in the office area and the other on the roof, programmed to record averages every 10 minutes from 1 minute's readings.

The existing damaged SCF was removed from the windows previously to the experimental procedure (Figure 5b) due to the difficulty of accurately modelling a damaged material in a simulation program.



a) b)

Figure 5. a) Location of the office of the case study in the floorplan b) Removal of the existing damaged SCF

The operational energy (*OE*) of the building was assessed through dynamic simulation using the SketchUp and EnergyPlus software, and the different scenarios of the glazing system were dimensioned using *Window and Optics* tools from the Lawrence Berkeley National Laboratory. Figure 6 shows the 3D geometric BES model of the building.

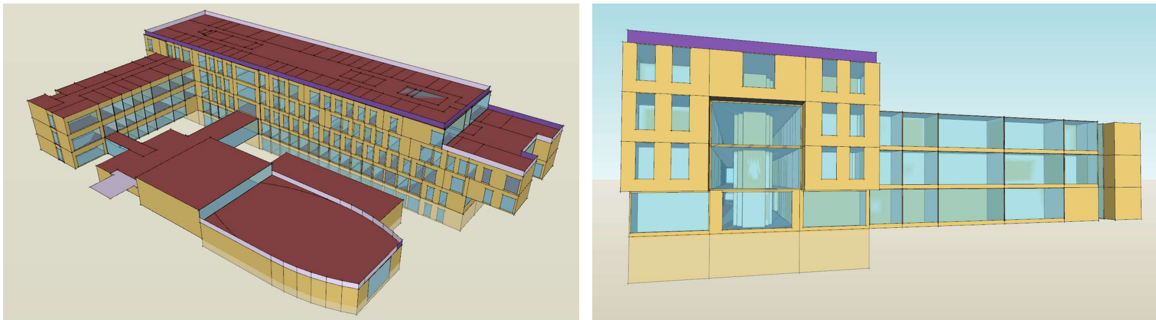


Figure 6. Geometrical model of the building executed on a SketchUp 3D modelling program

The performance of the BES model was verified by comparing the indoor temperature of the reference office obtained through simulation and experimental procedures during both heating and cooling periods. The experimental collected values of outdoor temperature as well as the global and diffuse radiation were set under the weather data file format of EnergyPlus for the verification procedure. This verification was performed to assess the suitability of the input data related to the construction characteristics (building geometry, building orientation, materials properties), and which are invariable input parameters in the BES model. Once a good agreement between simulated and experimentally values is achieved, the subsequent simulation to predict the results of the different retrofitting solution was carried in nominal conditions.

The experimental, $T_{i,exp}$, and simulated, $T_{i,sim}$, values of the indoor air temperature of the reference office without the damaged SCF for a selection of working and non-working days are shown in Figure 7 during one week of the heating and cooling periods. A monthly average verification is also shown in Figure 8 and Table 2 presents the standardized statistical indexes - Normalized Mean Bias Error, N_{MBE}, and Coefficient of variation of the Root-Mean Square Error, $C_{v,RMSE}$ [44] - calculated for all the days of the experimental procedure during the summer and winter periods and the threshold values of the statistical indexes accepted in existing literature [54]–[56]. A similar methodology for the verification of simulated models' accuracy was applied in previous studies [31], [33].

It can be observed in Figure 7 that the highest difference between the experimental and the simulated values are related to the unpredictability of the usage of the HVAC system associated with the occupant's behavior or preference on those specific days. Although the building has a centralized program system to maintain a set-point temperature during working hours, occupants can manually regulate indoor temperature through dedicated fan coils in their offices. The fact that it is not possible to identify evident periods during working-hours with constant indoor temperature in the office (Figure 7), shows the inconsistency of occupant's individual behavior in the HVAC usage, observing even cases where no HVAC is used. Indeed, intermittent periods of use of the HVAC system is common in Mediterranean climates. During the weekend, when there is no occupancy and the HVAC is turned off, a smaller discrepancy between experimental and simulation results is observed. The statistical index $C_{v,RMSE}$ (Table 2) supports these conclusions, since during the non-working days the values are ~70-75% lower than the ones observed during the working days. A thorough analysis by the monthly averages of the indoor experimental and simulated temperatures shown in Figure 8 indicate that, even though both values present some differences, the daily average values are very similar to each other. In Figure 8 it is also possible to observe the discrepancy of the maximum and minimum daily values of the experimental and simulated temperatures, especially in the cooling season (August and September) that are related to the unpredictability of the usage of the HVAC system. In Table 2 it is possible to observe that the calculated values of the statistical indexes for the indoor temperature of the BES model are both lower than the threshold limits for model calibrations [54]–[56], which indicates a good fit between simulation and experimental data. The differences in N_{MBE} and $C_{v,RMSE}$ were considered satisfactory for subsequence comparative analyses of different solutions for the glazing façade.

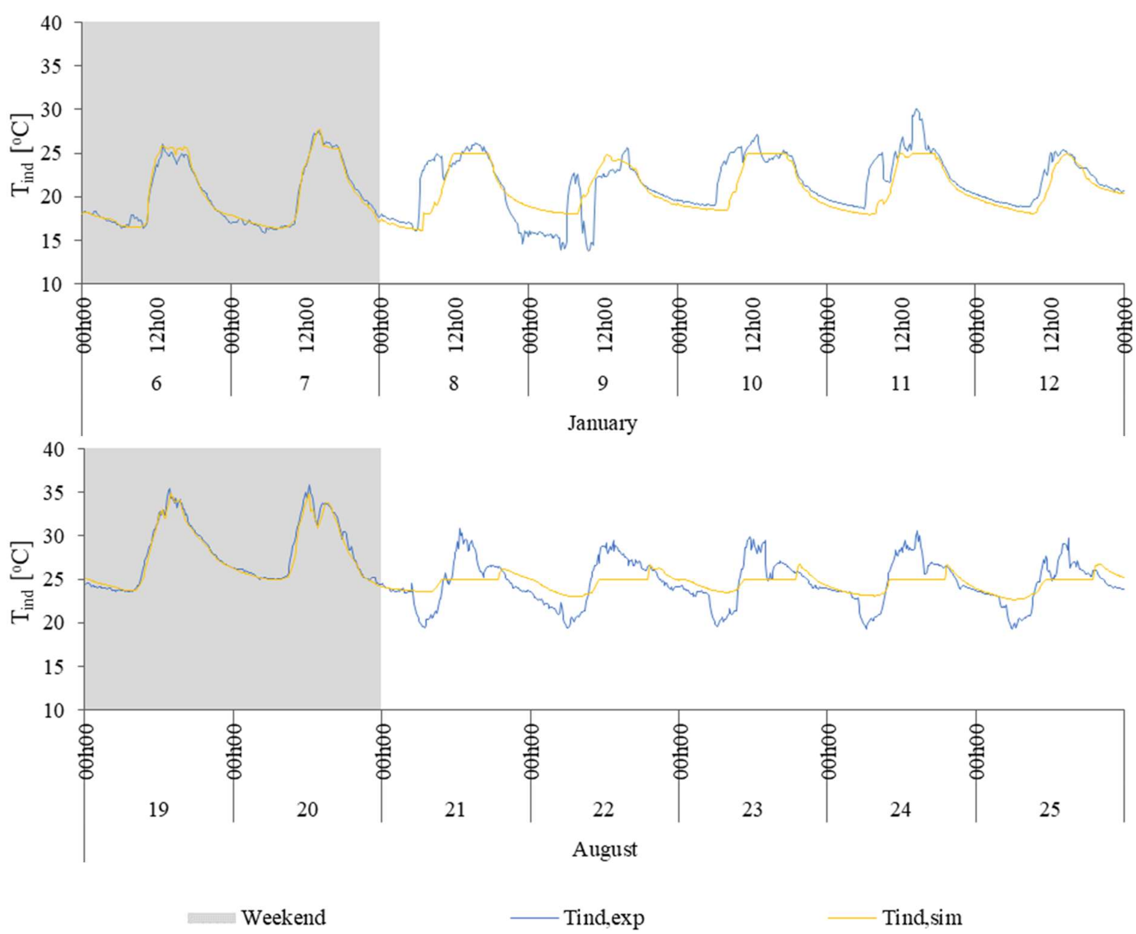


Figure 7. Simulated, $T_{ind,sim}$, and experimental, $T_{ind,exp}$, values of indoor temperature during one week of the heating (from 6th to 12th of January) and cooling (from 19th to 25th of August) periods

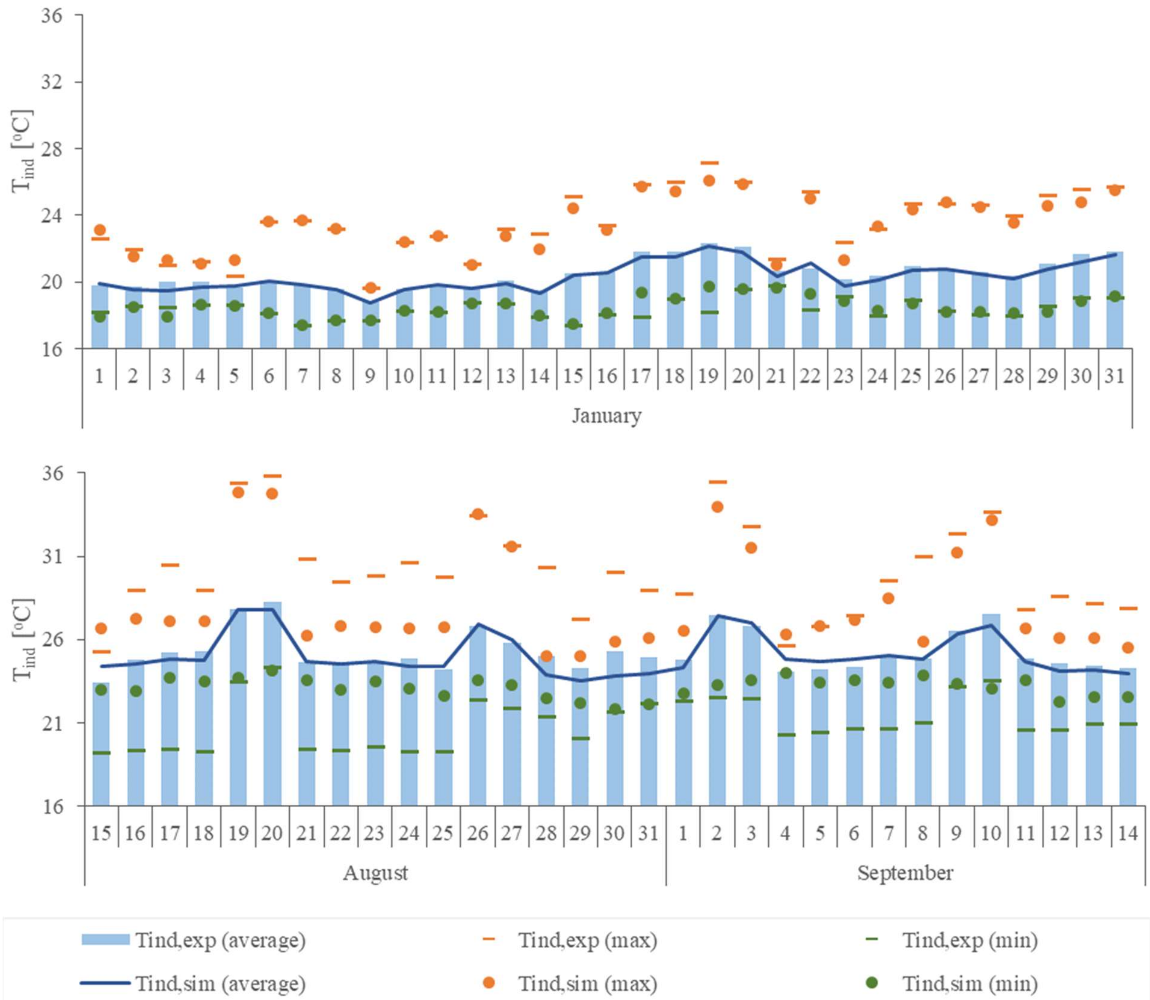


Figure 8. Monthly average verification of the simulated, $T_{ind,sim}$, and experimental, $T_{ind,exp}$, values of indoor temperature

Table 2. N_{MBE} and $C_{v,RMSE}$ of the office room indoor temperature and threshold values during the cooling and heating periods for working and non-working days for all the days of the experimental campaign

	Cooling period		Heating period		Threshold limits		
	Working days	Non-working days	Working days	Non-working days	[54]	[55]	[56]
N_{MBE} [%]	-0.79	-2.48	-0.13	-0.11	±10	±10	±5
$C_{v,RMSE}$ [%]	8.43	2.52	10.18	2.55	±30	±30	±20

5. Results and discussion

In this study, two alternative retrofitting scenarios for double-glazing systems were studied: the application of SFC on the external surface of the glass and the replacement of the existing window by a new one as shown in Table 3. SCF A is a reflective film with silver color, 0.050mm thickness, and is manufactured through several layers of metallized polyester attached with a pressure sensitive acrylic adhesive and a siliconized Polyethylene Terephthalate (PET) protective liner as finishing layer. SCFs B and C are less reflective than SCF A due to the metal free manufacturing process which consists of multi layers of Polymethyl Methacrylate (PMMA) and PET with a pressure sensitive acrylic adhesive and a siliconized PET protective liner as finishing layer. Both films B and C are spectrally selective with 0.05mm thickness and different solar transmittances (higher for SCF C) and while SCF B shows a tinted dark-yellow appearance when installed, SCF C shows a clear appearance and does not affect the color of existing glazing.

Table 4 shows the optical and thermal properties considering the different scenarios calculated through Window and Optics programs [40]. Window has a broad database of glasses, applied films, coatings, and frames that allow calculating total window thermal performance indices. Nonetheless, it is not always straightforward to select and analyse different films due to the extensive amount of available data. Optics complements the Window program since it provides access to a database of various applied films organized in a specific list, simplifying the process of selecting the films to be investigated.

Table 3. Retrofitting scenarios

Scenario (*Sc*)	Description
Sc2 Solar control films (SCFs)	Application on the external layer of the original window without the damaged SCF
Sc2.1 SCF A	Application of a reflective SCF
Sc2.2 SCF B	Application of a spectrally selective SCF (lower solar transmittance)
Sc2.3 SCF C	Application of a spectrally selective SCF (higher solar transmittance)
Sc3 New window (NW)	With an air gap
Sc3.1 NW	Increase the thickness of the glass layer and decrease the solar and visible transmittance

Table 4. Thermal and optical characteristics of the existing window and the alternative retrofitting scenarios: solar transmittance, τ_{sol}, solar (front) reflectance, $\rho_{f,sol}$, absorptance (front), α_l, visible transmittance, τ_{vis}, visible (front), $\rho_{f,vis}$, and (back), $\rho_{b,vis}$, reflectance, thermal transmittance, U (W/m^2.K), and solar factor, g

Scenario (Sc_{i})	mm	τ_{sol} [%]	$\rho_{f,sol}$ [%]	α_l [%]	τ_{vis} [%]	$\rho_{f,vis}$ [%]	$\rho_{b,vis}$ [%]	U [W/m^2.K]	g [%]
Sc1 Existing window (*EW*)	32	36.6	16.6	40.9	56.4	14.2	9.82	1.4	48.0
Sc2 Solar control films (SCFs)									
Sc2.1 SCF A	32	5.9	58.5	29.8	10.6	57.8	30.4	1.4	12.1
Sc2.2 SCF B	32	11.9	25.4	52.5	24.5	8.35	11.5	1.4	23.4
Sc2.3 SCF C	32	19.4	28.1	37.2	41.5	15.1	12.1	1.4	29.3
Sc3 New window (NW)									
Sc3.1 NW	38	12.0	25.6	48.6	28.4	23.3	26.4	1.1	29.6

The *OE* for the different scenarios of the glazing system was calculated, using the BES model with the original synthetic weather data of Lisbon's city [39], considering the lighting, heating and cooling energy use, from Monday to Friday and from 8h00 to 18h00. The HVAC system was set to turn-on when the indoor temperature exceeds the thermal comfort range of temperatures for Portugal (18 °C to 25 °C), according to [57]. The energy consumption with water heating and appliances was considered independent of the type of the window system used on the façade and therefore was not considered in the *OE* calculation.

5.1 Operational energy

Figure 9 shows the lighting, heating, cooling, and the total variation of the operational energy, *ΔOE*, between the retrofitting solution and the original glazing calculated per m^2 of floor area during the 40 years life-cycle, for: *Sc2.1* retrofitting using SCF A, *Sc2.2* retrofitting using SCF B, *Sc2.3* retrofitting using SCF C, *Sc3.1* replacement with a NW.

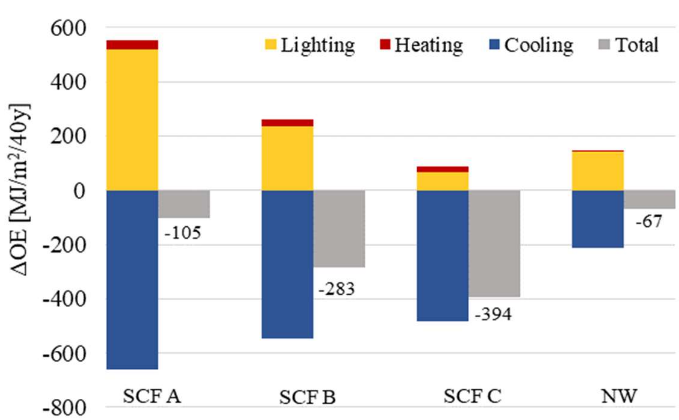


Figure 9. Lighting, heating, cooling, and total variation of the operational energy, *ΔOE*, per m^2 of floor area

When comparing the retrofitting scenarios for the glazing area of the building (Figure 9), it is possible to observe that:

- all retrofitting solutions are feasible to increase the energy efficiency of the building of the case study during the operational stage since they all show negative values of the *ΔOE* when compared to the original scenario of the glazing system without SCF, *Sc1*;
- SCF B (*ΔOE*= -283 MJ/m^2/40years) and SCF C (*ΔOE* = -394 MJ/m^2/40years) show a higher *ΔOE* when compared to SCF A (*ΔOE*= -105 MJ/m^2/40years). These differences can be explained by the higher visible transmittance coefficient and solar factor of SCF B (τ_{vis}= 24.5; g= 23.4) and SCF C (τ_{vis}= 41.5; *g*= 29.3) when compared to SCF A (τ_{vis}= 10.6; *g*= 12.1). In fact, previous studies [33], [58] show that the application

of SCFs on glazing systems decrease the cooling energy use and increase the heating and lighting energy use of glazing systems. For the building of the case study, the cooling energy use represents ~62% of the total *OE* and the lighting about ~29%. Therefore, retrofitting solutions with higher light-to-solar gain ratios (τ_{vis}/g) as SCF B (τ_{vis}/g= 1.05) and SCF C (τ_{vis}/g= 1.42) show a higher variation of the operational energy by decreasing the solar gains in a higher proportion than the decrease of the visible transmittance.

- SCFs show higher ΔOE when compared to the alternative scenario of full replacement of the EW, especially in the variation of the cooling energy. The higher insulation of the NW (1.1W/m^2.K vs. 1.4W/m^2.K, see Table 4) decreased the heat losses during the night periods when compared to the other 3 SCFs, trapping heat during the night, and requiring more cooling load in the summer periods and less heating load in the winter periods in the first hours of the working-hours. These results are in accordance with O'Neill et al. [22] who concluded that the combination of low U values and high solar factor in windows allows the entry of more solar radiation during the day and less heat escapes during the night, increasing the energy needs with HVAC consumption.

It is worth highlighting that a preliminary study that considered 3 NWs with comparable optical and thermal properties to the 3 SCFs applied in the existing glazing was performed. It was concluded that the results of the 3 NWs were very similar due to their similar optical and thermal characteristics and therefore only one of the NW is presented in this study for comparison purposes.

5.2 Carbon footprint and economic costs

Following the methodology described in chapter 3,

Table 5 and Table 6 show the list and the quantity of resources (materials consumed and total hours of labor) and corresponding disaggregated basic prices involved in *Sc3.1* and *Sc2.3* scenarios for a single building window unit (1.012 m^2). The simple unit economic cost of the retrofit work of a window is equal to the sum of the products of the quantities and the respective basic prices.

EE and *CF* were obtained by converting the original measure unit of each basic price (meters, square meters, tons, cubic meters) into cubic meters, so that the established density available in supporting documents can be applied. Then, equations (2-5) are applied to obtain *EE* and *CF* of each resource and the respective totals of the retrofit work of the window.

Table 5. Disaggregated resources and basic prices, economic and environmental costs, and carbon dioxide emissions for the replacement of a window unit

Price code	Qu.	Un.	Resource Description	Economic Cost EC [€/un]	EC [€]	Environmental Cost EE [MJ/un]	EE [MJ]	CF [38] [$kgCO_2eq$/un]	CF [$kgCO_2eq$]
01KLV90001	1.012	m^2	Labor in selective demolition of window with aluminum profiles						
TP00100	0.3	h	Special labor	18.28	5.55	0.00	0.00	0.00	0.00
06WWR80060	1.012	m^2	Received from received from façade fences.						
WW80010	0.09	kg	TIPS 20x100 cm	7.42	0.68	0.00	0.00	0.00	0.00
AGM00500	0.03	m^3	Cement mortar M5 (1:6) CEM II / A-L 32.5 N						
GW00100	0.263	m^3	Water	0.55	0.00	31.06	0.25	7,40	0,06
GC00200	0.258	t	Cement II / A-L 32,5 N in sacks	92.54	0.72	3778.06	29.59	786,09	53,34
AA00300	1.102	m^3	Gross sand	6.53	0.22	141.43	4.73	15,29	4,35
TP00100	1.030	h	Special labor	18.28	0.57	0.00	0.00	0.00	0.00
TP00200	0.350	h	Professional workmanship	19.23	6.81	0.00	0.00	0.00	0.00
TA00100	0.350	h	Assistant	18.42	6.52	0.00	0.00	0.00	0.00
11LVA80050	1.012	m^2	Window folding aluminum lacquer type IV with TBB (>3m^2)						
TO01600	0.15	h	Workmanship carpentry	19.23	2.92	0.00	0.00	0.00	0.00
TP00100	0.17	h	Special labor	18.28	3.14	0.00	0.00	0.00	0.00
KA01100	3	m	Pre-fence tube steel galvanized fixed or fixed	3.11	9.44	18.43	55.95	1,16	0,59
KL80300	1	m^2	White lacquered aluminum folding window with TBB	230.00	232.76	1 595.96	1 615.11	99,09	297,27
RW01900	3	m	Sealing gasket	1.30	3.95	6.12	18.59	0,13	0,40
WW00300	1	u	Complementary material or specials pieces.	0.55	0.56	2.65	2.68	0,16	0,48
12LTI80016	0.533	m^2	Thermoacoustic lighting colorless polished lenses 8+14+8+8mm, air chamber 14mm.						
VL04650	1	m^2	Double reflective and colorless under emissive and solar control 8+14+8+8mm, (air chamber)	43.22	23.04	138.74	73.95	1,58	0,84
VW01500	3	m	Neoprene "U" profile	0.40	0.64	91.09	145.65	2,62	7,85
TO01700	0.85	h	Glass worker	19.23	8.71	0.00	0.00	0.00	0.00
Total (*EC*, *EE*, and *CF*)					306.24		1946.50		365.17

Table 6. Disaggregated resources and basic prices, economic and environmental costs and carbon dioxide emissions for a window retrofitted with SCF C

Price code	Qu.	Un.	Resource Description	Economic Cost EC [€/un]	EC [€]	Environmental Cost EE [MJ/un]	EE [MJ]	Carbon Footprint CF [38] [$kgCO_2eq$/un]	CF [$kgCO_2eq$]
20FCL90026	1.012	m^2	Outdoor window cleaning						
TP00100	0.08	h	Special labor	18.28	1.48	0.00	0.00	0.00	0.00
JL00100	0.08	h	Cleaning materials	0.70	0.06	2.87	0.23	0.23	0.00
12WWW00001	1.012	m^2	Installation of outdoor window protection film						
TP00300	0.3	h	Special labor	19.23	5.77	0.00	0.00	0.00	0.00
HW01000	3	m^2	Scaffolding for sale in façade	0.40	1.20	0.00	0.00	0.00	0.00
090	1	m^2	Sheet for windows, exterior placement, prestige 70	58.00	58.70	48.58	49.16	3.90	11.70
WW00300	2	u	Complementary material or pzas. specials	0.30	0.61	2.65	5.37	0.16	0.32
Total (*EC*, *EE* and *CF*)					67.81		54.76		12.02

Table 7 shows the economic costs (*EC*), embodied energy (*EE*) and carbon footprint (*CF*) obtained for the retrofitting scenarios normalized per m^2 of floor area without considering the contribution of the operational energy. The values of *EC*, *EE*, and *CF* for *Sc2* are indicated for each installation of the films as well as for the four necessary installations in the life cycle studied. *Sc3* comprehends only one replacement in the starting point of the life cycle under scope, so the values of *EC*, *EE* and *CF* in the beginning and end of the life cycle are the same.

Table 7. Economic costs, *EC*, and embodied energy, *EE*, and carbon footprint *CF*, excluding the contribution of operational energy for the 4 retrofitting solutions per m^2 of floor area

Scenario (Sc_i.)	EC_{ini} [€/m^2/10y]	EE_M+EE_P [MJ/m^2/10y]	CF_M [kgCO_2eq/m^2/10y]	*EC (w/o OE)* [€/m^2/40y]	EE_M+EE_P [MJ/m^2/40y]	CF_M [kgCO_2eq/m^2/40y]
Sc2 SCFs	One installation in 10 years			Four installations in 40 years		
Sc2.1 SCF A	2.69	4.64	1.06	11.72	18.57	4.26
Sc2.2 SCF B	6.57	5.85	1.30	28.65	23.39	5.20
Sc2.3 SCF C	6.67	5.39	1.18	29.08	21.54	4.73
Sc3 NW	One replacement in 40 years					
Sc3.1 NW	30.12	191.46	35.93	30.12	191.46	35.93

The results show that during the life cycle period, the *EC* of SCFs B and C are very similar to the one of the NW and the *EC* of those 3 retrofitting solutions are, in turn, ~2.5 times higher than the *EC* of SCF A. The EE of retrofitting scenario *Sc2* shows the lowest value for the reflective film SCF A (18.57 MJ/m^2/40y) and the highest one for the spectrally selective film SCF B (23.39 MJ/m^2/40y). The average of the *EE* of the three films is ~89% lower than the *EE* of the NW and the *CF* of the retrofitting scenarios *Sc2* and *Sc3* is 4.4 to 5.3 times higher than the value of the *EE* of the retrofitting solutions, evidencing a high relationship between these two indicators during the *Product* and *Construction* stages.

5.3 Energy, economic and environmental analysis

Table 8 shows the operational, *OE*, and embodied, *EE*, energy, and the life cycle energy, *LCE*, associated with the retrofitting scenarios per m^2 of floor area. The ratio between the embodied energy and the life cycle energy is given by the following formula: *EE/LCE*.

Comparing the values of the *OE* of the retrofitting solutions, it is possible to conclude that the *OE* varies between 420.84 and 551.66 MJ/m^2/40y. And, as discussed in Section 5.1, SCF C shows the lowest value of *OE* because of the higher light-to-solar gain ratio (τ_{vis}/g= 1.42) when compared to the other solutions. On the other hand, comparing the *LCE* results for the four retrofitting solutions, it is possible to conclude that the *LCE* is lower using SCFs mainly due to the lower values of *EE* when compared with the total replacement of the window. Observing the proportion of embodied energy to life cycle energy, the embodied energy presents the highest and the lowest percentage of *LCE* for NW (25.8%) and for the reflective SCF A (3.3%), respectively.

Table 8. Life cycle energy for the 4 retrofitting solutions: operational, *OE*, and embodied, *EE*, energy, life cycle energy, *LCE*, and the ratio of the embodied energy to the LCE, *EE/LCE*

Scenario (Sc_i.)	*EE* [MJ/m²/40y]	*OE* [MJ/m²/40y]	*LCE* [MJ/m²/40y]	*EE/LCE* [%]
Sc2 SCFs				
Sc2.1 SCF A	18.57	536.63	555	3.3
Sc2.2 SCF B	23.39	465.19	489	4.8
Sc2.3 SCF C	21.54	420.84	442	4.9
Sc3 NW				
Sc3.1 NW	191.46	551.66	743	25.8

Table 9 shows the economic, *EC*, and environmental, *CF*, costs related to the retrofitting solutions during the 40 years life-cycle. SCF A and NW present the lowest (48 €/m^2/40y) and the highest (1046 €/m^2/40y) economic costs of the 4 retrofitting solutions, respectively. It is worth noticing that although SCF A shows the highest operational energy costs (35.83 €/m^2/40y) of the three films, the total economic cost is the lowest of the retrofitting solutions due to the lower production and construction works' economic costs associated with this film (11.72 €/m^2/40y).

Observing the results of the CF_M it is possible to conclude that the three SCFs generate almost the same amount of CO_2 equivalent per m^2 of floor area (average of 4.73 kgCO_2eq/m^2/40y). In terms of the NW, the CF_M (35.93 kgCO_2eq/m^2/40y) is almost eight times higher than the average of the three films. The total *CF* of the four retrofitting solutions show that the three SCFs analysed produce almost half of the amount of CO_2 equivalent per m^2 when compared to a new window replacement during the 40 years life cycle (which corresponds to the useful life of windows).

Table 9. Economic and environmental costs, *EC* and *CF*, respectively, for the 4 retrofitting solutions: inicial, C_i, and operational, EC_{OE}, economic costs; material, CF_M, and operational, CF_{OE}, carbon footprint

Scenario (Sc_i.)	EC_{OE} [€/m²/40y]	*EC* [€/m²/40y]	CF_M [kgCO_2eq/m²/40y]	CF_{OE} [kgCO_2eq/m²/40y]	*CF* [kgCO_2eq/m²/40y]
Sc2 SCFs					
Sc2.1 SCF A	35.83	48	4.26	42.14	46
Sc2.2 SCF B	31.06	60	5.20	36.53	42
Sc2.3 SCF C	28.10	57	4.73	33.05	38
Sc3 NW					
Sc3.1 NW	36.84	67	35.93	43.32	79

Figure 10 shows the results of combined operational and embodied energy and the economic and environmental costs that allow to identify the best solution from a multiple-criteria decision analysis for window retrofitting of non-residential buildings in temperate Mediterranean climates. The combined results of operational and embodied energy lead to the identification of the lower life cycle energy and carbon footprint retrofitting scenario - SCF C (*LCE*= 442 MJ/m^2/40y, *CF*= 38 kgCO_2eq/m^2/40y). It is also worth noticing that SCF A shows the lowest *EC* (48 €/m^2/40y) and the highest *LCE* and *CF* (*LCE*= 555 MJ/m^2/40y, *CF*= 46 kgCO_2eq/m^2/40y) among the three SCFs, resulting in the best SCF investment from an economic point of view, and the least effective from an energy and environmental standpoint.

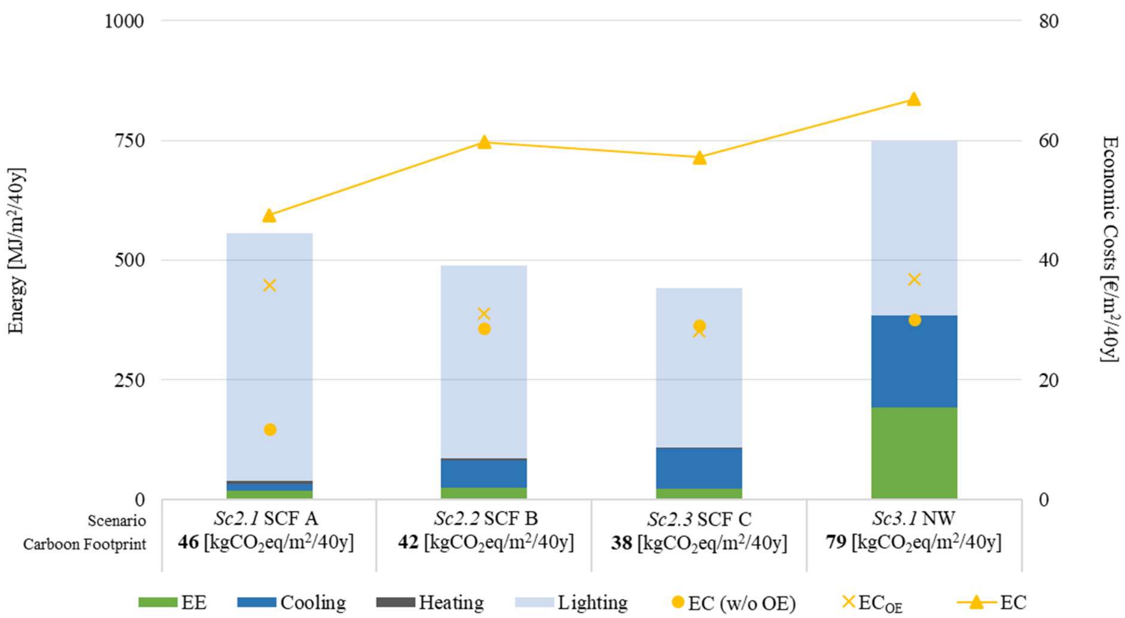


Figure 10. Operational energy with *lighting*, *heating,* and *cooling*, embodied energy, *EE*, economic costs, *EC*, and carbon footprint for the retrofitting solutions per m^2 of floor area during the life cycle period

6. Conclusions

The purpose of this work was to describe and assess the energy, environmental and economic impacts alternative retrofitting scenarios for glazing areas of existing non-residential buildings using a LCA comparative study and to quantify the relative importance of embodied and operational energy associated with solar control films (SCFs). The scenario of three SCFs (SCFs A, B and C) with different thermal and optical properties and the scenario of a new window (NW) replacement were the retrofitting scenarios considered in this study to improve the energy efficiency of an existing office building located in Lisbon, considered as the case study. The methodology used considers the building as a previously finished and consolidated system and therefore the life cycle stages of the LCA do not involve the building itself but only the new construction solutions and the economic and environmental costs associated with each one of the four retrofitting solutions (three SCFs and one NW). The established life cycle period was set in 40 years (useful life of windows) to enable a comparable timeline between the two alternative retrofitting scenarios.

This study showed that different retrofitting scenarios such as SCFs and NWs can reduce the total operational energy, while meeting the current standards of thermal and visual comfort requirements in the work environment. The operational energy results showed that retrofitting solutions with higher light-to-solar gain ratios (τ_{vis}/g), such as SCFs B and C, exhibit higher operational energy savings by decreasing the solar gains in a higher proportion than the decrease of the visible transmittance and therefore the reduction of the cooling energy needs is much higher than the increase of the lighting and heating energy needs. The higher insulation of the new window (U=1.1 W/m^2.K) was also a factor that contributed to the lowest operational energy savings of this solution when compared to the ones obtained for SCFs (U=1.4W/m^2.K), since it lowered the heat losses during the night periods, trapping heat during the night, and requiring more cooling load in the morning periods.

As expected, all retrofitting solutions increased the embodied energy of the building since retrofitting interventions have impacts associated with the production and transportation of the new components related to each retrofitting solution. The found embodied energy for the four retrofitting solutions revealed that the NW shows the highest value in the life cycle period when compared to the three SCFs (~9 times higher than the average of the embodied energy of the films). In fact, the lower values of the life cycle energy of SFCs are related to the lower values of *EE* and *OE* of the 3 SCFs when compared to that of the NW.

The Carbon Footprint results showed that the carbon equivalent generated to produce the films is between 38-46 kgCO_2eq per m^2 of floor area for 40 years, whereas to manufacture NW is 2 times higher than the ones of the films.

Window retrofitting solutions such as SCF A with lower production and construction works' costs can be economic advantageous. However, while this film was found to be the best investment from an economic point of view when compared to the other three retrofitting solutions, it also yielded the highest operational and environmental costs.

The results of this study show the importance of a combined operational and embodied energy analysis for retrofitting solutions of existing glazing systems and presents valuable information to support the decision-making process towards more efficient and sustainable buildings. Comprehensive studies of retrofitting scenarios should be thoughtfully investigated before retrofitting interventions to promote accurate estimations on the life cycle energy and awareness of possible environmental impacts during its life cycle.

Acknowledgments

The authors would like to thank the building management team and the office occupant for providing the space and conditions for the installation of the experimental equipment as well as the IMPERSOL company for the application of the films and technical support. The authors would like to extend their thanks to the MSc student Ricardo Coelho for the support during the experimental campaign and the support of the CERIS Research Institute, Instituto Superior Técnico, Universidade de Lisboa. The first and second authors wish to acknowledge, respectively the support of the FCT (Foundation for Science and Technology) PhD Grant FCT PD/BD/127848/2016 and mobility grant VIPPIT-2019-VI, of the VI Plan Propio of the University of Seville, who have made this research possible.

References

[1] I. R. M. Association, *Architecture and Design: Breakthroughs in Research and Practice*, vol. 1 edition. 2019.

[2] N. P. Dunphy and J. E. Morrissey, "Optimization of construction supply chains for greenhouse gas reduction.," in *Architecture and Design: Breakthroughs in Research and Practice*, 2015, pp. 627–657.

[3] C. Thormark, "A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential," *Build. Environ.*, vol. 37, no. 4, pp. 429–435, Apr. 2002.

[4] F. Asdrubali, P. Baggio, A. Prada, G. Grazieschi, and C. Guattari, "Dynamic life cycle assessment modelling of a NZEB building," *Energy*, vol. 191, p. 116489, 2020.

[5] A. Koezjakov, D. Urge-Vorsatz, W. Crijns-Graus, and M. van den Broek, "The relationship between operational energy demand and embodied energy in Dutch residential buildings," *Energy Build.*, vol. 165, pp. 233–245, Apr. 2018.

[6] G. A. Blengini and T. Di Carlo, "Energy-saving policies and low-energy residential buildings: An LCA case study to support decision makers in Piedmont (Italy)," *Int. J. Life Cycle Assess.*, vol. 15, no. 7, pp. 652–665, 2010.

[7] J. Macias, L. Iturburu, C. Rodriguez, D. Agdas, A. Boero, and G. Soriano, "Embodied and operational energy assessment of different construction methods employed on social interest dwellings in Ecuador," *Energy Build.*, vol. 151, pp. 107–120, Sep. 2017.

[8] S. Seo, G. Foliente, and Z. Ren, "Energy and GHG reductions considering embodied impacts of retrofitting existing dwelling stock in Greater Melbourne," *J. Clean. Prod.*, vol. 170, pp. 1288–1304, 2018.

[9] K. I. Praseeda, B. V. V. Reddy, and M. Mani, "Embodied and operational energy of urban residential buildings in India," *Energy Build.*, vol. 110, pp. 211–219, Jan. 2016.

[10] J. Mourão, R. Gomes, L. Matias, and S. Niza, "Combining embodied and operational energy in buildings refurbishment assessment," *Energy Build.*, vol. 197, pp. 34–46, Aug. 2019.

[11] M. Tarantini, A. D. Loprieno, and P. L. Porta, "A life cycle approach to Green Public Procurement of building materials and elements: A case study on windows," *Energy*, vol. 36, no. 5, pp. 2473–2482, 2011.

[12] C. R. Iddon and S. K. Firth, "Embodied and operational energy for new-build housing: A case study of

construction methods in the UK," *Energy Build.*, vol. 67, pp. 479–488, Dec. 2013.

[13] A. Vilches, A. Garcia-Martinez, and B. Sanchez-Montañes, "Life cycle assessment (LCA) of building refurbishment: A literature review," *Energy Build.*, vol. 135, pp. 286–301, 2017.

[14] M. G. Gomes, A. J. Santos, and A. M. Rodrigues, "Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study," *Build. Environ.*, vol. 71, pp. 47–59, Jan. 2014.

[15] M. C. Singh and S. N. Garg, "Energy rating of different glazings for Indian climates," *Energy*, vol. 34, no. 11, pp. 1986–1992, 2009.

[16] M. G. Gomes, A. M. Rodrigues, and J. A. Bogas, "Numerical and experimental study of the optical properties of venetian blinds," *J. Build. Phys.*, vol. 36, no. 1, pp. 7–34, 2012.

[17] D. H. . Li, J. C. Lam, C. C. . Lau, and T. . Huan, "Lighting and energy performance of solar film coating in air-conditioned cellular offices," *Renew. Energy*, vol. 29, no. 6, pp. 921–937, May 2004.

[18] D. H. W. Li, T. N. T. Lam, S. L. Wong, and E. K. W. Tsang, "Lighting and cooling energy consumption in an open-plan office using solar film coating," *Energy*, vol. 33, no. 8, pp. 1288–1297, Aug. 2008.

[19] K. H. Kim, "A comparative life cycle assessment of a transparent composite façade system and a glass curtain wall system," *Energy Build.*, vol. 43, no. 12, pp. 3436–3445, 2011.

[20] F. Pomponi, P. A. E. Piroozfar, R. Southall, P. Ashton, P. Pirozfar, and E. R. P. Farr, "Life cycle energy and carbon assessment of double skin façades for office refurbishments," *Energy Build.*, vol. 109, pp. 143–156, 2015.

[21] S. Citherlet, F. Di Guglielmo, and J. B. Gay, "Window and advanced glazing systems life cycle assessment," *Energy Build.*, vol. 32, no. 3, pp. 225–234, 2000.

[22] R. O'Neill, A. Window, S. Kenway, and P. Dargusch, "Integrated operational and life-cycle modelling of energy, carbon and cost for building façades," *J. Clean. Prod.*, vol. 286, p. 125370, 2021.

[23] M. Asif, T. Muneer, and J. Kubie, "Sustainability analysis of window frames," *Build. Serv. Eng. Res. Technol.*, vol. 26, no. 1, pp. 71–87, 2005.

[24] A. Sinha and A. Kutnar, "Carbon footprint versus performance of aluminum, plastic, and wood window frames from cradle to gate," *Buildings*, vol. 2, no. 4, pp. 542–553, 2012.

[25] S. Saadatian, F. Freire, and N. Simões, "Embodied impacts of window systems: A comparative assessment of framing and glazing alternatives," *J. Build. Eng.*, vol. 35, p. 102042, 2021.

[26] J. Pereira, M. G. Gomes, A. M. Rodrigues, H. Teixeira, and M. Almeida, "Small-scale field study of window films ' impact on daylight availability under clear sky conditions," *J. Façade Des. Eng.*, 2020.

[27] Y. Chen, G. Hou, H. Xie, and W. Chan, "In-site experimental measurement of energy-saving performance for solar-control film on single window glass," *IAQVEC 2007 Proc. - 6th Int. Conf. Indoor Air Qual. Vent. Energy Conserv. Build. Sustain. Built Environ.*, vol. 1, pp. 47–53, 2007.

[28] C. Li, J. Tan, T.-T. Chow, and Z. Qiu, "Experimental and theoretical study on the effect of window films on building energy consumption," *Energy Build.*, vol. 102, pp. 129–138, Sep. 2015.

[29] K. M. Yousif, "Solar gain in buildings in hot climatic zones: case study of a selected Iraqi building using window solar control film," *ISESCO J. Sci. Technol.*, vol. 11, no. 19, pp. 43–50, 2015.

[30] A. Bahadori-Jahromi, A. Rotimi, A. Mylona, P. Godfrey, and D. Cook, "Impact of window films on the overall energy consumption of existing UK hotel buildings," *Sustain.*, vol. 9, no. 5, pp. 1–23, 2017.

[31] J. Pereira, M. Glória Gomes, A. Moret Rodrigues, and M. Almeida, “Thermal, luminous and energy performance of solar control films in single-glazed windows: Use of energy performance criteria to support decision making,” *Energy Build.*, vol. 198, pp. 431–443, Sep. 2019.

[32] E. Moretti and E. Belloni, “Evaluation of energy, thermal, and daylighting performance of solar control films for a case study in moderate climate,” *Build. Environ.*, vol. 94, pp. 183–195, 2015.

[33] H. Teixeira, M. Glória Gomes, A. Moret, and J. Pereira, “Thermal and visual comfort, energy use and environmental performance of glazing systems with solar control films,” *Build. Environ.*, vol. 168, p. 106474, Oct. 2020.

[34] T. Nagahama, T. Sato, T. Harima, and J. Shimizu, “Optical properties and field test results of spectrally-selective solar control window film that enables not increasing downward reflection,” *Energy Build.*, 2017.

[35] I. 14040:2006; I. O. for Standardization, “ISO. Environmental Management — Life Cycle Assessment — Principles and Framework.” Geneve.

[36] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology,” *International Journal of Life Cycle Assessment*, vol. 21, no. 9. pp. 1218–1230, 2016.

[37] M. Marrero and A. Ramirez-De-Arellano, “The building cost system in andalusia: Application to construction and demolition waste management,” *Constr. Manag. Econ.*, vol. 28, no. 5, pp. 495–507, 2010.

[38] C. Rivero Camacho, J. Pereira, M. G. Gomes, and M. Marrero, “Huella de carbono como instrumento de decisión en la rehabilitación energética. Películas de control solar frente a la sustitución de ventanas,” *Rev. Hábitat Sustentable*, vol. 8, no. 2, pp. 20–31, 2018.

[39] U.S. Department of Energy, “EnergyPlus™ Version 9.0.1 Documentation,” *U.S. Dep. Energy*, vol. Input Outp, p. 2691, 2018.

[40] C. Curcija, S. Vidanovic, R. Hart, J. Jonsson, and R. Mitchell, “WINDOW Technical Documentation,” *Wind. Envel. Mater. Group, Lawrence Berkeley Natl. Lab.*, 2018.

[41] “The 3M Quality Promise. Energy Products Distribution. Available online in December 2020 <https://epdwindowfilm.com/warranty/>.” .

[42] PORDATA - Base de Dados Portugal Contemporâneo, “Preços eletricidade para utilizadores domésticos e industriais (Euro/ECU),” 2019. [Online]. Available: https://www.pordata.pt/Europa/Preços+da+electricidade+para+utilizadores+domésticos+e+industriais+(Euro+ECU)-1477-313029.

[43] T. L. Garwood, B. R. Hughes, M. R. Oates, D. O’Connor, and R. Hughes, “A review of energy simulation tools for the manufacturing sector,” *Renew. Sustain. Energy Rev.*, vol. 81, no. August 2017, pp. 895–911, 2018.

[44] Tarek E . Bou-Saada & Jeff S . Haberl, “An improved procedure for developing calibrated hourly simulation models,” *Proc. 5th Int. IBPSA Conf.*, 1995.

[45] “Regulamento de Desempenho Energético dos Edifícios de Habitação (REH), Decreto-Lei 118/2013 de 20 de Agosto 2013,” *Diário da República*, vol. 159, pp. 4988–5005, 2013.

[46] A. Martínez-Rocamora, J. Solís-Guzmán, and M. Marrero, “Ecological footprint of the use and maintenance phase of buildings: Maintenance tasks and final results,” *Energy Build.*, vol. 155, pp. 339–351, 2017.

[47] J. Solís-Guzmán, M. Marrero, and A. Ramírez-De-Arellano, “Methodology for determining the ecological footprint of the construction of residential buildings in Andalusia (Spain),” *Ecol. Indic.*, vol. 25, pp. 239–249,

2013.

[48] M. Marrero, A. Fonseca, R. Falcon, and A. Ramirez-de-Arellano, "Schedule and Cost Control in Dwelling Construction Using Control Charts," *Open Constr. Build. Technol. J.*, vol. 8, no. 1, pp. 63–79, 2014.

[49] Department of Energy & Climate Change, "Greenhouse gas reporting - Conversion factors 2015," 2015.

[50] E. C. B. (ECB), "Eurosystem staff macroeconomic projections for the euro area," no. December 2009, pp. 1–19, 2019.

[51] E. C. B. (ECB), "Mercados financeiros," no. 1, p. 2020, 2020.

[52] A. M. Rodrigues, M. Santos, M. G. Gomes, and R. Duarte, "Impact of natural ventilation on the thermal and energy performance of buildings in a Mediterranean climate," *Buildings*, vol. 9, no. 5, 2019.

[53] F. R. M. Kottek, J. Grieser, C. Beck, B. Rudolf, "World map of the Köppen-Geiger climate classification updated," *Meteorol. Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.

[54] ASHRAE, "ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings," *Am. Soc. Heating, Refrig. Air-Conditioning Eng. Atlanta, GA, USA*, 2002.

[55] FEMP, "M&V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4.0," no. November, pp. 1–306, 2015.

[56] IPMVP New Construction Subcommittee, "International Performance Measurement & Verification Protocol: Concepts and Options for Determining Energy Savings in New Construction - Volume III," *Washington, DC, USA*, vol. III, no. April, pp. 1–249, 2003.

[57] 1.ª série — N.º 159 — 20 de agosto de 2013 Diário da República, "Decreto-Lei n.º 118/2013," *Diário da República*, pp. 4988–5005, 2013.

[58] J. Pereira, M. Glória Gomes, A. Moret Rodrigues, and M. Almeida, "Thermal, luminous and energy performance of solar control films in single-glazed windows: Use of energy performance criteria to support decision making," *Energy Build.*, vol. 198, 2019.