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EVALUATION OF ENERGY EFFICIENT REFURBISHMENT OF RESIDENTIAL BUILDINGS IN SOUTHERN EUROPE BASED ON THE COST-OPTIMAL METHODOLOGY

Ana Brandão de Vasconcelos*, António Santos and António Cabaço

Buildings Department, National Laboratory for Civil Engineering (LNEC), Av. do Brasil 101, 1700-066 Lisbon, Portugal

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Corresponding author:
Ana Brandão de Vasconcelos,

ABSTRACT

In line with the European Energy Performance of Building Directive (EPBD), this paper aims to calculate the cost-optimal energy performance of a residential building in southern Europe, more precisely in Portugal, taking into consideration thermal and lighting (daylighting and artificial lighting) refurbishment solutions. The economic calculation method used considers the initial investment costs, the running costs (including annual maintenance costs, operational costs, energy costs and periodic replacement costs), greenhouse gas emissions costs and disposal costs. The results obtained for the energy needs allow choosing the cost-optimal package of refurbishment measures. It is shown in this paper the relevance of daylighting and artificial lighting solutions for the users' indoor comfort, for the building energy consumption and, consequently, for the overall costs during the building life span. From the daylighting and artificial lighting point of view, the most influent factors are the type and solar optical glazing and the shading devices properties. For the adopted reference building under Lisbon climate conditions and a North-South orientation façade, light-coloured external roller blinds and single tinted blue-green glass solutions are the ones that lead, in the majority of cases, to simultaneously lower values of global costs and energy consumptions.

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INTRODUCTION

In November 2016, the European Commission presented the "Clean Energy for All Europeans" Package (Clean Energy Package) composed of a set of legislative proposals in the areas of energy efficiency, renewable energy and the internal electricity market. This package aimed to promote energy transition in the coming decades, with a view to fulfilling the Paris Agreement on climate change and global warming (European Commission, 2016). In this context, the European Union approved (Regulation (EU) 2018/1999, 2018) a set of targets aimed at achieving, by 2030, a share of energy from renewable sources in gross final consumption of 32%, an increase in energy efficiency of 32.5%, a reduction of greenhouse gas (GHG) emissions from 1990 levels of 40% and achieving 15% of electricity interconnections. Achieving these targets promotes both the competitiveness, modernisation and sustainability of the energy system at European level, without compromising the objectives of economic development and job creation. In December 2019, the European Commission presented the European Green Deal, shaped as a new growth strategy for transforming the European Union into an equitable and prosperous society with a modern, competitive and resource-efficient economy by, among other things, achieving zero net GHG emissions in 2050. The European Green Pact has identified the renovation of buildings, both public and private, as a key initiative to boost energy efficiency in the sector and meet the decarbonisation objectives.

In this context, and in order to pursue this ambition of energy gains and economic growth, the European Commission published, in October 2020, a new strategy to boost renovation called "A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives" (European Commission, 2020), under which the construction sector emerges as one of the largest consumers of energy in Europe due to the energy inefficiency of its stock of about 75%, being also responsible for one third of GHG emissions in the European Union. For these reasons, a renovated and improved European building stock is considered to be a fundamental building block for a decarbonised and clean energy system. Therefore, a reduction on the energy consumption and the use of energy from renewable sources in the buildings sector are needed, as a way to reduce the Union's energy dependency and greenhouse gas emissions. Several efforts are currently being done to define methods to optimize energy performance in buildings. Directive 2010/31/EU (Energy Performance of Buildings Directive (EPBD) recast) (Directive 2010/31/EU, 2010) is one such example at European level and aims to ensure energy savings and CO2 emission reduction. This Directive establishes a framework for the definition of a cost-optimal methodology: an assessment that allows different levels of energy intervention to be compared under distinct macroeconomic scenarios. Otherwise, this methodology allows establishing a relationship between the performance and the correspondent costs of energy refurbishment solutions, thus enabling to determine the most cost-efficient package of solutions throughout the life cycle, named the cost-optimal level.

By supporting refurbishment building solutions from the results of this methodology, cost-effective energy refurbishments are being promoted. On the basis of the implementation of the EPBD 2010/31/EU (Directive 2010/31/EU, 2010), the authors have undertaken a number of research studies aimed to apply the EPBD cost-optimal methodology to Portuguese buildings (Brandão de Vasconcelos, 2015; Brandão de Vasconcelos *et al*., 2014; Brandão de Vasconcelos, Pinheiro, *et al*., 2016; Brandão de Vasconcelos, Pinheiro, Manso, *et al*., 2015a). Other authors (Aguacil *et al*., 2017; Ascione *et al*., 2014; Ballarini *et al*., 2017; Fernandez-Luzuriaga *et al*., 2021; Ortiz *et al*., 2016) have also applied the cost-optimal methodology to other type of buildings under different climatic and local conditions. Usually thermal refurbishment measures, such as insulation, windows and glazing improvements, are taken into account in the studies that consider the cost-optimal methodology. It is not so often found the influence of artificial lighting energy consumption on the overall costs and, therefore, on the choice of the cost-optimal package of solutions to be applied to buildings. Natural and electric lighting are indisputably essential aspects of the indoor environmental comfort in buildings. Those aspects can also positively influence the energy efficient performance of buildings, as long as daylight is suitably collected and distributed to the interior spaces and that electric lighting is also properly designed. Furthermore, the advantages of daylight on the health and well-being of buildings users have been established, but those advantages are not considered in the traditional approaches to the use of daylight in buildings (Santos, 2014). In this regard, in order to attain appropriate comfort conditions and energy efficiency, the daylighting and electric lighting designers must consider several aspects that can improve the use of daylight, without harming further features of the building design such as thermal comfort or supplementary use of energy for lighting, heating or cooling. For example, the cautious and thorough choice of the glazing and shading devices can have an important effect on the final comfort and energy performance of buildings. Hence, it makes sense to take these aspects into consideration to find the cost-optimal solution that encompasses a balance between all the referred types of energy consumption, while preserving suitable levels of indoor comfort and overall performance of the building (Santos, 2011).

Some studies analyse the occupant control over lighting systems (Mahmoudzadeh *et al*., 2021) and the possibilities and approaches to lighting control (Wagiman *et al*., 2020), comparing the various control techniques used to determine their performance. In most lighting studies, the economic aspect is not assessed. Some studies combine the energy and economic aspect to support the optimisation of retrofit solutions, but only consider street lighting solutions (Beccali *et al*., 2019; Carli *et al*., 2018) or lighting systems and their energy consumption (Belany *et al*., 2021; Bonomolo *et al*., 2017), not assessing the effect of construction solutions on the building lighting energy consumption. Therefore, this paper aims to study the impact of daylighting and artificial lighting measures in determining the cost-optimal level and highlights their relevance in the overall costs during the lifetime of the building. In Section 1, this paper sets out the main objectives of the research work. Section 2 continues with the importance of daylighting and artificial lighting solutions for the determination of the cost-optimal level. The application of the cost-optimal methodology and the discussion of the results is done in Section 3 and Section 4, respectively. Finally, in Section 5, the conclusions of the whole research work are presented.

The relevance of natural and electric lighting refurbishment actions in the calculation of the cost-optimal level: In the framework of climate changes and global warming scenarios, it is vital to prove that the conscious use of natural light can improve the global energy efficiency in buildings. Additionally, it is also important to make available consistent calculation procedures that allow the building design team to guarantee that energy efficiency without harming the adequacy of the indoor daylight environment. A consistent and operative analysis methodology should also take into account aspects such as: the main characteristics of the local climate, the combined effects of the electric lighting and shading systems on the final daylighting conditions and energy consumption and the behaviours of occupants with regard to these systems (Galasiu *et al*., 2007; Galasiu, A. D.; Reinhart, C. F.; Swinton, M. C.; Manning, 2005; C. F. Reinhart, 2004; Santos, 2011, 2014). The main purpose of natural light in buildings is to contribute to a better luminous atmosphere that safeguards the most suitable lighting environments for carrying out the visual tasks (Santos, 2014). The adequacy of these lighting environments comprises the following aspects: i) adequate levels and spatial distribution of indoor daylight illuminances, ii) the assurance of visual comfort conditions for the occupants and iii) the additional (personal) advantages due to the use of daylight as a replacement for of electric light and the possibility of visual communication with the outdoor environment through daylight apertures. The use of daylight in buildings can also play an important role as an energy efficient technology if its energy effects are properly assessed, preferably, throughout the design stage. The energy impacts due to the use of daylight can be a major challenge and design issue in areas where clear or almost clear skies prevail during significant parts of the year (Santos, 2011). In fact, the average climatic characteristics of Portugal can potentially lead to, either summer thermal discomfort due to excessive overheating through windows, if the most adequate shading strategies are not implemented, or to additional cooling energy to overcome the aforementioned summer thermal discomfort (Gomes *et al*., 2014a).

COST-OPTIMAL METHODOLOGY

The cost-optimal methodology for establishing a relationship between the performance and the correspondent costs of energy refurbishment solutions comprises five phases. The first phase consists of the definition of the Reference Building(s) (RB). Then, in the second phase, the energy efficiency measures to be applied to the established RB are identified. In the third phase the final and primary energy needs of the RB are calculated, both with and without the application of energy efficiency measures. In the fourth phase an economic calculation method (life cycle costing) is applied over the lifetime of the building for a calculation period of 30 years. Finally, in the fifth phase the cost optimal level of energy performance (cost optimal package) is determined (Brandão de Vasconcelos, Pinheiro, *et al*., 2016). In previous studies, the cost optimal level was determined considering different thermal refurbishment measures applied to a Portuguese Reference Building (RB) (Brandão de Vasconcelos, 2015; Brandão de Vasconcelos, Cabaço, *et al*., 2016; Brandão de Vasconcelos, Pinheiro, Cabaço, *et al*., 2015; Brandão de Vasconcelos, Pinheiro, *et al*., 2016). Following these studies, daylighting and artificial lighting solutions were added to the thermal refurbishment solutions. This new set of solutions was applied to a Portuguese RB with the most representative characteristics and building solutions of the residential buildings built in Lisbon between 1961 and 1990. This RB is a 7-storey residential building with two dwellings per floor, each with 78 m2 of internal floor area, and was characterised in the publication Brandão de Vasconcelos, *et al*. (Brandão de Vasconcelos, Pinheiro, Manso, *et al*., 2015b).

Cost-optimal methodology application: The energy efficiency measures selected to be applied to the building are within two groups of solutions: thermal refurbishment of the building envelope and daylighting and artificial lighting measures. Table 1 lists the various thermal and daylighting/lighting refurbishment measures that were adopted to be applied in the building envelope. These groups of measures directly influence the energy consumption for heating, cooling and lighting, contributing to the overall quality of the indoor environment. The ones that influence exclusively the heating and cooling consumptions are the following: two types of ground floor solutions (vinyl coating and marble natural stone); one type of roof solution (with different thermal insulation thicknesses); and, two types of wall solutions (ETICS and 7cm brick wall, with different thermal insulation thicknesses). Among the solutions chosen, the ones affecting the lighting energy consumption are those related to the fenestration, namely the window frames, glazing and shadings devices, as follows: ten types of measures for the windows (aluminium, with and without thermal break, and PVC window frames, all with glazing with different functional properties); and, one type of external shading device (plastic external roller blind), with two types of colour (light-coloured and dark-coloured). The choice of fenestration solutions took into account the following factors: i) suitability for use in residential buildings; ii) the use of energy efficient materials in the heating season and particularly in the cooling season; iii) an acceptable "visual impact" in refurbishment situations; iv) a reasonably high luminous transmittance (TL) of glazing; and v) the use of materials/solutions compatible with other domains of the refurbishment process (Pina dos Santos & Matias, 2007). The selection of glazing materials ranged from single tinted blue-green (with intrinsic spectrally selective properties) to more advanced low-e and spectrally selective low-e glazing materials. The chosen window frames and shading devices are the most commonly used in Portuguese residential buildings. As for the shading devices, traditional light-coloured and dark-coloured (mostly white and "medium grey" coloured) plastic/metallic external roller blinds were selected (Figure 1 and Figure 2). For comparison purposes, the dimensions of windows were kept constant and equal to those of the reference building. The complete set of fenestration solutions used in the simulations is described in Table 1.

In reference to EN 12464-1:2021 (European Committee for Standardisation (CEN), 2021), the illuminance level required in the working place is 500 lx. In the analysis performed, the gap between natural illuminance and the required illuminance level was assured though the use of artificial lighting. The user profile took also into account the following aspects: 8h/day out for working during workdays, 24h/day on weekends and blinds operation depending on the season. An important input for EnergyPlus simulations is the definition of reliable and consistent user schedules. These aspects try to replicate the real user behaviour for the operation of shading devices and manual on/off lighting controls (Santos, 2011). These behavioural aspects can have a significant impact on visual and thermal comfort and energy consumption (C. Reinhart & Voss, 2003). The solutions listed in Table 1 were combined with each other resulting in 14,784 packages of measures. In order to obtain the cost-optimal level, the energy needs for heating, cooling and artificial lighting were calculated using the EnergyPlus software. For that, the Portuguese EPBD thermal regulations for Residential Buildings – REH, 2013 (REH, 2013) and the climatic conditions of Lisbon (Portugal) were taken into account. The global costs of the packages of measures applied to the building were then calculated.

Table 1. Refurbishment measures applied to the building

Measure ID	Measure location	Solution
		Existing solution
Wind 00	Window	Aluminium window frames (no thermal break) with single clear glass, 6mm thick
Roof 00	Roof	Sloped roof without thermal insulation, with a horizontal solid reinforced concrete slab, 0.23m thick, with ceramic roof tiles
Floor 00	Ground floor	Ground floor without thermal insulation with a solid reinforced structure slab, 0.23 thick, and application wooden blocks coating directly applied on the screed
Wall 00	External wall	Single walls of hollow ceramic brick of 30x20x22mm without thermal insulation, plastered and painted
		Proposed solutions
Wind 01	Window	Aluminium window frame (without thermal break) – single tinted blue-green glass, 6mm thick
Wind 02	Window	Aluminium window frame (without thermal break) – double clear glass (4mm+6mm thick) + 10mm air space
Wind 03	Window	Aluminium window frame (without thermal break) – double clear glass (4mm+6mm low-e thick) + 10mm air space
Wind 04	Window	Aluminium window frame (without thermal break) – double clear glass (4mm+6mm spectrally selective low-e thick) + 10mm air space
Wind 05	Window	Aluminium window frame (with thermal break) – double clear glass (4mm+6mm thick) + 10mm air space
Wind 06	Window	Aluminium window frame (with thermal break) – double clear glass (4mm+6mm low-e thick) + 10mm air space
Wind 07	Window	Aluminium window frame (with thermal break) – double clear glass (4mm+6mm spectrally selective low-e thick) + 10mm air space
Wind 08	Window	PVC window frame – double clear glass (4mm+6mm thick) + 10mm air space
Wind 09	Window	PVC window frame – double clear glass (4mm+6mm low-e thick) + 10mm air space
Wind 10	Window	PVC window frame – double clear glass (4mm + 6mm spectrally selective low-e thick) + 10mm air space
Roof 01	Roof	EPS 20mm thick over the concrete slab
Roof 02	Roof	EPS 30mm thick over the concrete slab
Roof 03	Roof	EPS 40mm thick over the concrete slab
Roof 04	Roof	EPS 60mm thick over the concrete slab
Roof 05	Roof	EPS 80mm thick over the concrete slab
Roof 06	Roof	EPS 100mm thick over the concrete slab
Floor 01	Ground floor	Vinyl floor coating without thermal insulation
Floor 02	Ground floor	Vinyl floor coating over EPS 20mm thick
Floor 03	Ground floor	Vinyl floor coating over EPS 30mm thick
Floor 04	Ground floor	Vinyl floor coating over EPS 40mm thick
Floor 05	Ground floor	Vinyl floor coating over EPS 60mm thick
Floor 06	Ground floor	Vinyl floor coating over EPS 80mm thick
Floor 07	Ground floor	Marble natural stone over EPS 20mm thick
Wall 01	Exterior wall	ETICS with 20mm of EPS from the outside of the existing exterior wall
Wall 02	Exterior wall	ETICS with 30mm of EPS from the outside of the existing exterior wall
Wall 03	Exterior wall	ETICS with 40mm of EPS from the outside of the existing exterior wall
Wall 04	Exterior wall	ETICS with 60mm of EPS from the outside of the existing exterior wall
Wall 05	Exterior wall	ETICS with 80mm of EPS from the outside of the existing exterior wall
Wall 06	Exterior wall	ETICS with 100mm of EPS from the outside of the existing exterior wall
Wall 07	Exterior wall	7cm brick wall from the inside of the existing exterior wall over EPS 20mm thick
Wall 08	Exterior wall	7cm brick wall from the inside of the existing exterior wall over EPS 40mm thick
Wall 09	Exterior wall	7cm brick wall from the inside of the existing exterior wall over EPS 60mm thick
Wall 10	Exterior wall	7cm brick wall from the inside of the existing exterior wall over EPS 80mm thick
Wall 11	Exterior wall	7cm brick wall from the inside of the existing exterior wall over EPS 100mm thick
Blind 01	Ext. shading device	Light-coloured plastic external roller blind
Blind 02	Ext. shading device	Dark-coloured plastic external roller blind

Fig. 1. Traditional Portuguese light-coloured external roller blind

Fig. 2. Traditional Portuguese dark-coloured external roller blind

In this study, the macroeconomic perspective was used (Aggerholm *et al*., 2011; Guidelines Regulation No 244, 2012). This macro perspective includes benefits and costs from “externalities”, such as climate change damages associated with carbon dioxide emissions. Strictly following the meaning of the EPBD for this perspective, the global cost of each package of solutions corresponds to the price paid by the end consumer, excluding all applicable taxes, subsidies and incentives, and including the initial investment costs, the sum of the annual costs for every year and the final value, as well as the disposal costs and the cost of global greenhouse gas (GHG) emissions. The global costs were determined using the Net Present Value method (Boermans *et al*., 2011), considering a discount rate of 3% (value recommended in different studies and EU regulation (Langdon, 2007; Regulation No 244, 2012; Rushing *et al*., 2013)). Figure 3 shows the cost-optimal curve that was found when evaluating all the combinations of measures listed in Table 1 for the building, from a macroeconomic perspective. The primary energy consumption represents the total energy consumed by all the 14 dwellings belonging to the building.

The lowest point of the curve (red dot) corresponds to the package of measures with the lowest global cost. The cost-optimal level with the same or similar costs corresponds to the one with the lowest primary energy consumption (circle dots with different colour levels). The part of the curve to the right of the cost-optimal level represents solutions that perform less well in both aspects (environmental and financial). The left part of the curve (rainbow coloured dots), starting at the cost-optimal level, represents the cost-optimal energy-performance levels for low and nearly zero energy buildings (nZEB) (Brandão de Vasconcelos, Santos, *et al*., 2016; Guidelines Regulation No 244, 2012). The cost-optimal level package of the building measures corresponds to Wind 00, Wall 00, Roof 04, Floor 01 and Blind 01. This package consists of the following measures for the refurbishment of the building envelope: replacement of the existing window with an aluminium window frame (without thermal break) with single clear glass 4mm thick, without intervention at the external wall, application of EPS, 60mm thick, on the concrete slab, application of vinyl floor covering without thermal insulation and a light-coloured plastic external roller blind. This global solution is, therefore, the most cost-efficient.

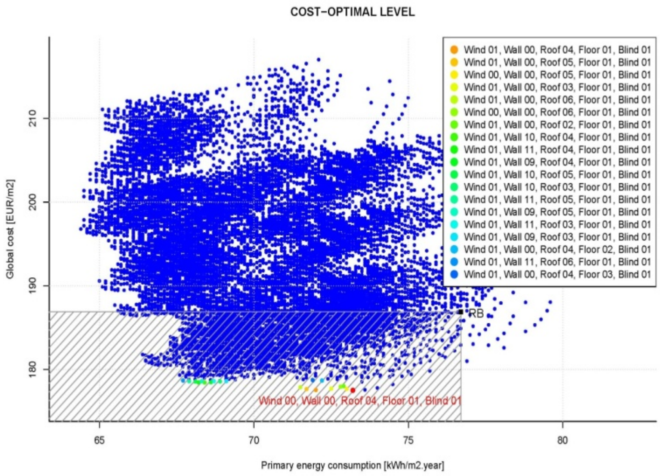

Fig. 3. Cost-optimal level

Although the cost-optimal package includes 4mm-thick single clear glass in its global solution, 85% of the cost-optimal level of packages with the same or similar costs but lower primary energy use (circular dots with rainbow colours) include the 6mm-thick single tinted blue-green glass solution (Brandão de Vasconcelos, Santos, *et al*., 2016). Within the scope of this research, these results take into account thermal and daylighting/artificial lighting aspects.

Costs breakdown: The costs of the measures or packages of measures applied to the RB may differ from country to country and from market to market. Table 2 illustrates costs for the Portuguese market associated with these measures. The investment costs, maintenance costs and replacement costs are obtained from the ProNIC (Protocol for Technical Information Standardisation in Construction) database (Monteiro *et al*., 2014) and are complemented by prices taken from construction bids and from LNEC database on construction prices (Manso, 2013) updated until 2017. The residual value of each measure is calculated based on the remaining lifetime of the last replacement of the measure until the end of the calculation period, assuming a linear depreciation over its lifetime. Table 2 shows the investment costs, maintenance costs, replacement costs and residual values for each measure for the whole calculation period (30 years). The price unit (€/m2) refers to the net internal floor of the dwelling. Figure 4 shows the global cost breakdown structure of the packages of measures listed in Figure 3 (packages with the same or similar costs as the cost-optimal package but with lower primary energy uses). These cost breakdown structures include not only the costs illustrated in Table 2 but also energy costs and GHG emission costs. The cost-optimal package of measures is labelled in red colour and it corresponds to the lowest global cost. A detailed calculation of all these costs and the methodology used is presented in Brandão de Vasconcelos *et al.* (2016), namely the durability of construction measures, maintenance activities and their periodicity, depreciation of materials, investments and energy costs forecasts, among others.

The global cost breakdown structure found for all the above mentioned packages considers a range of 34,0% to 38,0% for investment costs, a range of 5,6% to 6,5% for maintenance costs, a range of 4,0% to 4,4% for replacement costs, a range of 46,0% to 51,0% for energy costs, a range of 2,4% to 2,7% for GHG emissions costs and 2,9% to 3,2% for residual values. The energy cost category has the largest impact on the global cost structure, for which a Portuguese standard cooling/heating equipment with a value of 3,0 for its Energy Efficiency Rate (EER) and a value of 3,4 for its Coefficient of Performance (COP) (REH, 2013) and compact fluorescent lighting solutions for all rooms with an average luminous efficacy around 80% were considered.

Table 2. Costs of the measures for RB over the 30-year calculation period

Measure ID	Investment cost [€/m^2]	Maintenance cost [€/m^2]	Replacement cost [€/m^2]	Residual value [€/m^2]
Wind 00	50,90	4,06	0,00	7,27
Roof 00	0,00	0,00	0,00	0,00
Floor 00	0,00	7,69	7,94	1,98
Wall 00	0,00	6,04	0,00	0,00
Wind 01	52,60	4,06	0,00	7,21
Wind 02	54,68	4,06	0,00	7,51
Wind 03	56,95	4,06	0,00	7,83
Wind 04	68,29	4,06	0,00	9,45
Wind 05	69,80	4,06	0,00	9,67
Wind 06	72,07	4,06	0,00	9,99
Wind 07	83,41	4,06	0,00	11,61
Wind 08	62,24	4,06	0,00	8,59
Wind 09	64,51	4,06	0,00	8,91
Wind 10	75,85	4,06	0,00	10,53
Roof 01	0,61	0,00	0,00	0,15
Roof 02	0,92	0,00	0,00	0,23
Roof 03	1,18	0,00	0,00	0,29
Roof 04	1,75	0,00	0,00	0,44
Roof 05	2,32	0,00	0,00	0,58
Roof 06	2,87	0,00	0,00	0,72
Floor 01	5,93	0,00	3,95	2,90
Floor 02	6,53	0,00	4,36	3,20
Floor 03	6,81	0,00	4,55	3,33
Floor 04	7,08	0,00	4,74	3,47
Floor 05	7,63	0,00	5,11	3,75
Floor 06	8,16	0,00	5,48	4,01
Floor 07	14,60	0,00	0,00	3,61
Wall 01	3,94	7,83	0,00	0,00
Wall 02	4,09	7,83	0,00	0,00
Wall 03	4,21	7,83	0,00	0,00
Wall 04	4,48	7,83	0,00	0,00
Wall 05	4,74	7,83	0,00	0,00
Wall 06	5,00	7,83	0,00	0,00
Wall 07	3,72	7,83	0,00	0,93
Wall 08	3,98	7,83	0,00	1,00
Wall 09	4,25	7,83	0,00	1,06
Wall 10	4,52	7,83	0,00	1,13
Wall 11	4,77	7,83	0,00	1,19
Blind 01	5,60	0,49	3,82	2,80
Blind 02	5,60	0,49	3,82	2,80

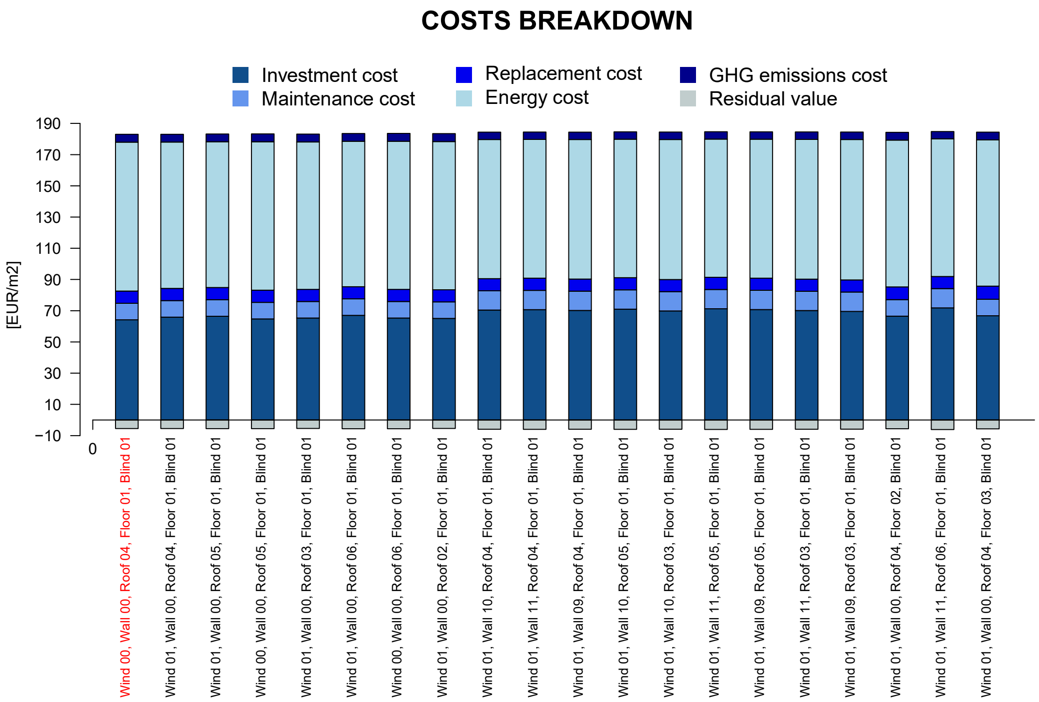

Fig. 4. Breakdown structure of the global cost of the packages of measures indicated in Figure 3

DISCUSSION OF RESULTS

In order to illustrate the influence of artificial lighting on the cost-optimal level, six figures are presented. Figure 5 to Figure 7 show the influence of the window solutions on the results obtained for the cost-optimal levels, considering separately the three types of energy consumption. Figure 5 shows the cost-optimal level considering just the cooling and heating energy needs. Figure 6 represents the cost-optimal level considering only the artificial lighting consumption. Figure 7 combines the information of the two previous figures (cooling & heating and artificial lighting). Similarly, Figure 8 to Figure 10 show the influence of the blinds solutions on the results of the cost-optimal levels, considering the same three types of energy consumption. In detail, Figure 5 to Figure 7 show the influence of window frames and different types of glazing, grouped in different colours, on the cost-optimal level. The first group of windows (Wind 01 to Wind 04) corresponds to aluminium frames without thermal break, the second (Wind 05 to Wind 07) refers to aluminium frames with thermal break and the third (Wind 08 to Wind 10) corresponds to PVC frames. Figure 5 and Figure 7 show similar cloud-point results. As shown, the results obtained in Figure 7Fig. correspond to a displacement of around 50 kWh/m^2.year in the x-axis (primary energy consumption) and about 70 €/m^2 in the y-axis (global cost) of the results in Figure 5. These displacements are due to the inclusion of artificial lighting consumptions (compact fluorescent lamps) and global costs in the results of Figure 7. In detail, the translations of the x-axis values are between 50,5 kWh/m^2.year and 50,9 kWh/m^2.year, as shown in Figure 6.

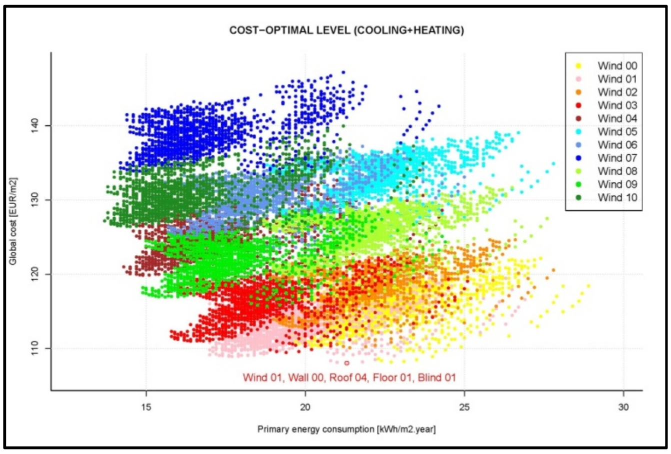

Fig. 5. Cost-optimal level (cooling & heating) – the influence of window frame and glazing

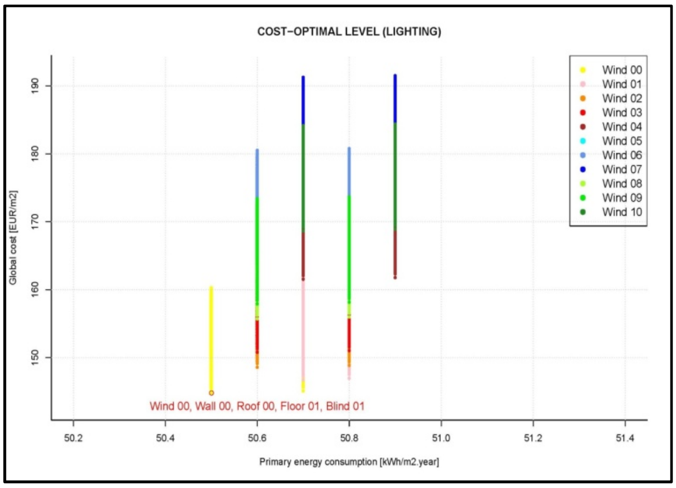

Fig. 6. Cost-optimal level (artificial lighting) – the influence window frame and glazing

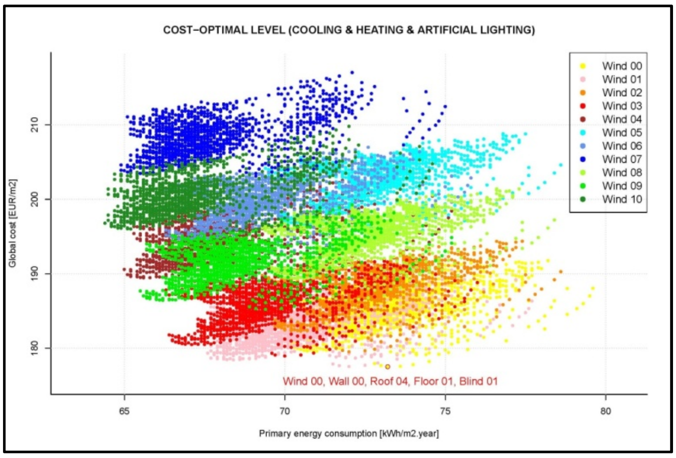

Fig. 7. Cost-optimal level (cooling & heating & artificial lighting) – the influence window frame and glazing

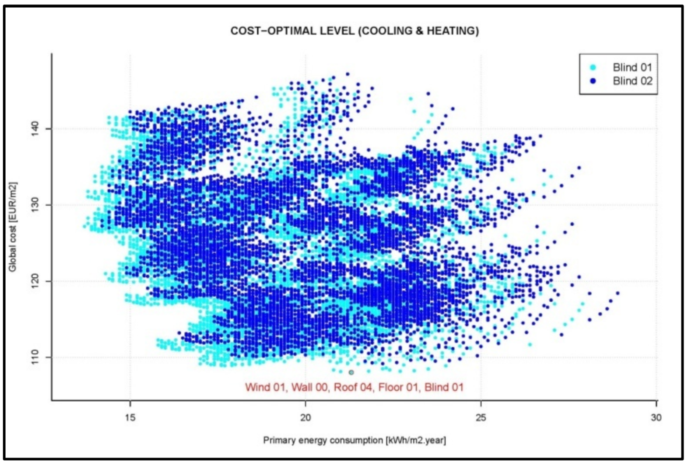

Fig. 8. Cost-optimal level (cooling & heating) – the influence of external blinds

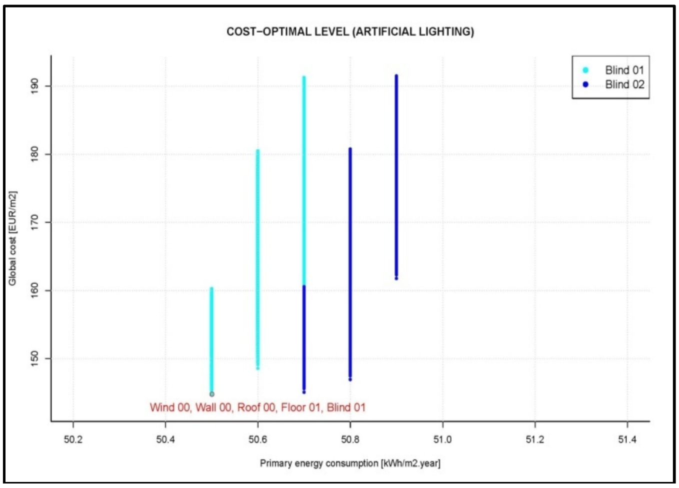

Fig. 9. Cost-optimal level (artificial lighting) – the influence of external blinds

Figure 7 shows that aluminium window frames without thermal break (yellow-orange spots – Wind 01, Wind 02 and Wind 03) lead to the lowest global costs and that aluminium window frames with thermal break (bluish spots – Wind 05, Wind 06 and Wind 07) lead to the highest. The global costs of PVC window frame solutions are between the two previous global costs found for the aluminium window frames solutions. From Figure 7 it is possible to identify the existence of “dot-cloud pairs”, each of which referring to the same window frame but to two different glazing solutions. It is the case of Wind 02 – Wind 03, Wind 05 – Wind 06 and Wind 08 – Wind 09 “dot-cloud pairs”.

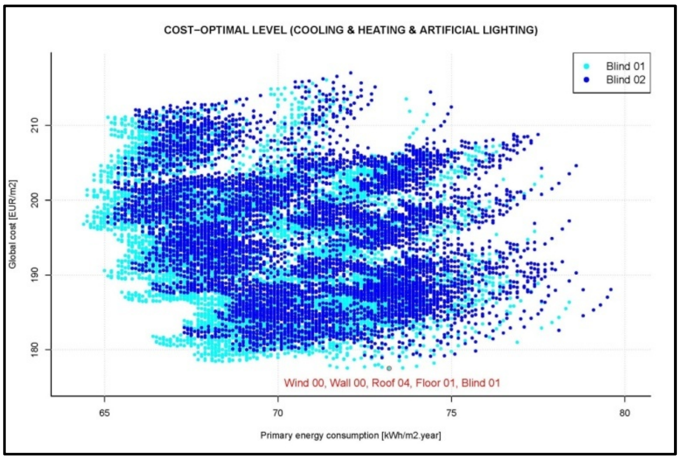

Fig. 10. Cost-optimal level (cooling & heating & artificial lighting) – the influence of external blinds

For each pair, the cloud on the right side corresponds to double clear glass solutions (Wind 02, Wind 05 and Wind 08) and the cloud on the left to double clear low-e glass solutions (Wind 03, Wind 06 and Wind 09). It can therefore be concluded that a window frame with double clear low-e glass solution has a lower global cost and a lower energy consumption than a window frame with double clear glass solution, considering the same glass thicknesses. Also from Figure 7, spectrally selective low-e glazing (darker colour spots – Wind 04, Wind 07 and Wind 10) lead to the lowest energy consumption (for cooling, heating and artificial lightning) for the building case study, while the global costs are the highest ones. Although not being part of the cost-optimal package of solutions found, the single tinted blue-green glass solution (Wind 01) is the one that leads, in the majority of cases, to lower values of global costs and energy consumptions. However, as it is discussed further ahead, it is a poor performer in terms of lighting consumption due to its lower daylight transmittance. In Figure 6, the artificial lighting energy consumption of the 14.784 packages of measures are represented. Five vertical lines are drawn, each one representing packages of solutions that have the same lighting energy consumption but different global cost depending on the solutions considered. These groups are the consequence of the glazing and blinds solutions effect in the energy lighting consumption. Although the identification of these five levels of lighting consumption, the actual difference between them is slight, of just 0.1 kwh/m^2.year between each level.

Regarding the type of blind (Figure 9), the first 2 vertical lines on the left and the middle one represent the results for the light-coloured blind (Blind 01) and the middle and the last 2 lines on the right represent the results for the dark-coloured blind (Blind 02). This means that for each type of blind, three levels of energy lighting consumption were obtained, corresponding to three performance categories of the analysed glazing. The leftmost results correspond to simple clear glass, the middle ones to double glazing and low emissive double glazing and the right ones to tinted blue-green glass and low emissive and spectrally selective double glazing. Therefore, for the RB in Lisbon, the glazing which provide lower lighting energy consumption, in each type of blind considered, are: i) the single clear glass (Wind 00), followed by ii) the double clear glass and the double clear glass low-e (Wind 02, Wind 05, Wind 08, Wind 03, Wind 06, Wind 09) and iii) the single tinted blue-green glass and the double clear spectrally selective low-e glass (Wind 01, Wind 04, Wind 07, Wind 10). From the conjugation of Figures 8 and 9, it is concluded that the spectrally selective low-e glass has the best performance in energy consumption considering heating and cooling (Figure 5) but the worst performance in terms of lighting (Figure 6). These results are coherent with the characteristics of the analysed glazing (solar heat gains, thermal insulation and daylight transmittance). It is also concluded that Wind 07 (aluminium window frame with thermal break, double glazing with 4mm clear glass / 10mm air space / 6mm spectrally selective low-e glass) is the solution that results in the highest global costs for all types of energy consumption considered (despite leading to lower energy consumption for heating and cooling). This high global cost is due to a high initial investment cost and a higher energy cost for lighting compared to the other glazing. Figure 8 to Figure 10Fig. show similar results to those presented in Figure 5 to Figure 7, but considering the effect of the blind solutions. From the results presented, it is possible to conclude that the light-coloured plastic external roller blind (Blind 01) leads to a lower energy consumption, both from the cooling & heating point of view and from the artificial lighting point of view, when compared to the dark-coloured one (Blind 02). This is due to the fact that Blind 01 has a higher reflectance and slightly higher visible transmittance values, but a lower solar transmittance when compared to the values of Blind 02. Therefore, Blind 02 allows a higher solar energy transmission (resulting in a higher cooling & heating energy consumption) but a moderately lower daylight transmission (resulting in a slightly higher energy consumption in artificial lighting). As a final remark, the most recommendable solutions for the building case study under Lisbon climate and N-S orientation are: aluminium window frames without thermal break, single tinted blue-green glazing (in most cases), light-coloured plastic external roller blinds, EPS 40mm to 100mm thick over concrete roof slabs, and non-thermally insulated vinyl floor covering on the ground floors. The cost-optimal wall solution can range from no intervention to the construction of 7cm brick wall from the inside of the existing exterior wall over 60mm to 100mm thick EPS.

CONCLUSIONS

This paper aimed to calculate the cost-optimal energy performance of a reference residential building in southern Europe, more precisely in Portugal, taking into consideration thermal and lighting (daylighting and artificial lighting) refurbishment solutions. A period of 30 years lifetime of the building was considered. The energy efficiency measures selected to be applied to the building are within two groups of solutions: thermal refurbishment of the building envelope and daylighting and artificial lighting measures. This paper continued previous studies, adding daylighting and artificial lighting measures to the set of energy refurbishment solutions. The added solutions not only have an impact on energy consumption for heating and cooling, but also on energy consumption for lighting. These new measures consisted of including other types of glazing and light-coloured/dark-coloured shading devices, as well as defining user profiles for blinds operation and artificial lighting usage. After applying the cost-optimal methodology, different charts were presented in order to illustrate the influence of artificial lighting and cooling and heating energy consumption on the cost-optimal level. Considering the building case study under Lisbon climate and N-S orientation, the main conclusions are the following:

- Aluminium window frames without thermal break lead to the lowest global costs and aluminium window frames with thermal break lead to the highest and PVC window frames solutions are between them;
- Window frames with double clear low-e glass solution have a lower global cost and a lower energy consumption than window frames with double clear glass solution, considering the same glass thicknesses;
- Spectrally selective low-e glazing lead to the lowest energy consumption (for cooling, heating and artificial lightning), while the global costs are the highest ones;
- Although not being part of the cost-optimal package of solutions found, the single tinted blue-green glass solution is the one that leads, in the majority of cases, to lower values of global costs and energy consumptions; however, it is a poor performer in terms of lighting consumption due to its lower daylight transmittance;
- The glazing which provide lower lighting energy consumption, in each type of blind considered, are the single clear glass, followed by the double clear glass and the double clear glass low-e, and then, by the single tinted blue-green glass and the double clear spectrally selective low-e glass;

- Spectrally selective low-e glass has the best performance in energy consumption considering heating and cooling, but the worst performance in terms of lighting, as it was expected from its characteristics (solar heat gains, thermal insulation and daylight transmittance);
- The light-coloured plastic external roller blind leads to a lower energy consumption, both from the cooling & heating point of view and from the artificial lighting point of view, when compared to the dark-coloured one;
- The aluminium window frame with thermal break, double glazing with 4mm clear glass / 10mm air space / 6mm spectrally selective low-e glass, is the solution that results in the highest global costs for all types of energy consumption considered (despite leading to lower energy consumption for heating and cooling).

REFERENCES

Aggerholm, S., Erhorn, H., Hitchin, R., Erhorn-Kluttig, H., Poel, B., Thomsen, K. E., & Wittchen, K. B. (2011). *Cost-optimal levels for energy performance requirements. The Concerted Action's input to the Framework Methodology*. Concerted action. Energy Performance of Buildings.

Aguacil, S., Lufkin, S., Rey, E., & Cuchi, A. (2017). Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data—A case study in Spain. *Energy and Buildings*, *144*, 42–60. https://doi.org/10.1016/j.enbuild.2017.03.047

Ascione, F., Bianco, N., De Stasio, C., Mauro, G. M., & Vanoli, G. P. (2014). A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. *Energy and Buildings*, *88*, 78–90. https://doi.org/10.1016/j.enbuild.2014.11.058

Ballarini, I., Corrado, V., Madonna, F., Paduos, S., & Ravasio, F. (2017). Energy refurbishment of the Italian residential building stock: energy and cost analysis through the application of the building typology. *Energy Policy*, *105*(January), 148–160. https://doi.org/10.1016/j.enpol.2017.02.026

Beccali, M., Bonomolo, M., Lo Brano, V., Ciulla, G., Di Dio, V., Massaro, F., & Favuzza, S. (2019). Energy saving and user satisfaction for a new advanced public lighting system. *Energy Conversion and Management*, *195*(May), 943–957. https://doi.org/10.1016/j.enconman.2019.05.070

Belany, P., Hrabovsky, P., & Kolkova, Z. (2021). Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings. *Energy Reports*, *7*, 2470–2483. https://doi.org/10.1016/j.egyr.2021.04.044

Boermans, T., Bettgenhäuser, K., Hermelink, A., & Schimschar, S. (2011). *Cost optimal building performance requirements. Calculation methodology for reporting on national energy performance requirements on the basis of cost optimality within the framework of the EPBD* (Issue May). European Council for an Energy Efficient Economy.

Bonomolo, M., Baglivo, C., Bianco, G., Congedo, P. M., & Beccali, M. (2017). Cost optimal analysis of lighting retrofit scenarios in educational buildings in Italy. *Energy Procedia*, *126*, 171–178. https://doi.org/10.1016/j.egypro.2017.08.137

Brandão de Vasconcelos, A. (2015). *Construção Energeticamente Sustentável - Metodologia de apoio à decisão em intervenções de reabilitação de edifícios*. Tese aprovada em provas públicas para obtenção do Grau de Doutor em Engenharia Civil na Universidade de Lisboa - Instituto Superior Técnico.

Brandão de Vasconcelos, A., Cabaço, A., Duarte Pinheiro, M., & Manso, A. (2016). The impact of building orientation and discount rates on a building refurbishment decision. EPBD Portuguese reference building case. *Energy Policy*, *91*, 329–340. https://doi.org/10.1016/j.enpol.2016.01.021

Brandão de Vasconcelos, A., Pinheiro, M. D., Cabaço, A., & Manso, A. C. (2015). Nível ótimo de rentabilidade de soluções de reabilitação energética da envolvente de edifícios. In Instituto Superior Técnico (Ed.), *Congresso CONPAT* (pp. 1–8). IST.

Brandão de Vasconcelos, A., Pinheiro, M. D., Manso, A. C., & Cabaço, A. (2014). Definição de uma metodologia de apoio à decisão na reabilitação sustentável de edifícios de betão armado. *5as Jornadas Portuguesas de Engenharia de Estruturas - JPEE 2014*, 1–16.

Brandão de Vasconcelos, A., Pinheiro, M. D., Manso, A. C., & Cabaço, A. (2015a). Energy efficient rehabilitation measures for the Portuguese residential buildings constructed in the 1960-1990 period. *1st International Symposium of Building Pathology - ISBP2015*, 8.

Brandão de Vasconcelos, A., Pinheiro, M. D., Manso, A., & Cabaço, A. (2015b). A Portuguese approach to define reference buildings for cost-optimal methodologies. *Applied Energy*, *140*, 316–328. https://doi.org/10.1016/j.apenergy.2014.11.035

Brandão de Vasconcelos, A., Pinheiro, M. D., Manso, A., & Cabaço, A. (2016). EPBD cost-optimal methodology: application to the thermal rehabilitation of the building envelope of a Portuguese residential reference building. *Energy and Buildings*, *111*, 12–25. https://doi.org/10.1016/j.enbuild.2015.11.006

Brandão de Vasconcelos, A., Santos, A., & Cabaço, A. (2016). Cost-optimal methodology: application to the thermal and lighting refurbishment of a Portuguese reference building. *41st IAHS World Congress - Sustainability and Innovation for the Future, 13-16th September*, 10.

Carli, R., Dotoli, M., & Pellegrino, R. (2018). A decision-making tool for energy efficiency optimization of street lighting. *Computers and Operations Research*, *96*, 223–235. https://doi.org/10.1016/j.cor.2017.11.016

Directive 2010/31/EU. (2010). The Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union, L153*.

European Commission. (2016). Clean Energy For All Europeans. In *COM(2016) 860 final*. European Commission.

European Commission. (2020). A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. In *COM(2020) 662 final*. European Commission.

European Committee for Standardisation (CEN). (2021). *Light and lighting - lighting of work places - Part 1: indoor work places*. EN 12464-1.

Fernandez-Luzuriaga, J., del Portillo-Valdes, L., & Flores-Abascal, I. (2021). Identification of cost-optimal levels for energy refurbishment of a residential building stock under different scenarios: Application at the urban scale. *Energy and Buildings*, *240*, 110880. https://doi.org/10.1016/j.enbuild.2021.110880

Galasiu, A. D., Newsham, G. R., Suvagau, C., & Sander, D. M. (2007). Energy saving lighting control systems for open-plan offices: A field study. *LEUKOS - Journal of Illuminating Engineering Society of North America*, *4*(1), 7–29. https://doi.org/10.1582/LEUKOS.2007.04.01.001

Galasiu, A. D.; Reinhart, C. F.; Swinton, M. C.; Manning, M. M. (2005). *Assessment of Energy Performance of Window Shading Systems at the Canadian Centre for Housing Technology*. Canadian Centre for Housing Technology. https://doi.org/https://doi.org/10.4224/20378354

Gomes, M. G., Santos, A. J., & Rodrigues, A. M. (2014a). Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study. *Building and Environment*, *71*, 47–59. https://doi.org/10.1016/j.buildenv.2013.09.003

Gomes, M. G., Santos, A. J., & Rodrigues, A. M. (2014b). Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study. *Building and Environment*, *71*, 47–59. https://doi.org/10.1016/J.BUILDENV.2013.09.003

Guidelines Regulation N^{o} 244. (2012). Guidelines accompanying Commission Delegated Regulation (EU) N.º 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings. *Official Journal of the European Union, 19 April 2012*, C 115/1-C 115/28.

Langdon, D. (2007). *Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology*. Davis Langdon Management Consulting.

Mahmoudzadeh, P., Afacan, Y., & Adi, M. N. (2021). Analyzing occupants' control over lighting systems in office settings using immersive virtual environments. *Building and Environment*, *196*(March), 107823. https://doi.org/10.1016/j.buildenv.2021.107823

Manso, A. C. (2013). *Informação Sobre Custos. Fichas de Atualização – dez 2012*. LNEC.

Monteiro, A., Mêda, P., & Martins, J. P. (2014). Framework for the coordinated application of two different integrated project delivery platforms. *Automation in Construction*, *38*, 87–99. https://doi.org/10.1016/j.autcon.2013.11.003

Ortiz, J., Fonseca i Casas, A., Salom, J., Garrido Soriano, N., & Fonseca i Casas, P. (2016). Cost-effective analysis for selecting energy efficiency measures for refurbishment of residential buildings in Catalonia. *Energy and Buildings*, *128*, 442–457. https://doi.org/10.1016/j.enbuild.2016.06.059

Pina dos Santos, C., & Matias, L. (2007). *Coeficientes de transmissão térmica de elementos da envolvente opaca dos edifícios*. ICT Informação Técnica, Edifícios - ITE 50, LNEC.

Regulamento Do Desempenho Energético Dos Edifícios de Habitação (REH) (2013).

Regulation (EU) 2018/1999. (2018). Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action. *Official Journal of the European Union, 21 December 2018*, L 328/1-L 328/77.

Regulation No 244. (2012). Commission Delegated Regulation (EU) N.º 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings. *Official Journal of the European Union, 21 March 2012*, L 81/18-L 81/36.

Reinhart, C. F. (2004). Lightswitch-2002: A model for manual and automated control of electric lighting and blinds. *Solar Energy*, *77*(1), 15–28. https://doi.org/10.1016/j.solener.2004.04.003

Reinhart, C., & Voss, K. (2003). Monitoring manual control of electric lighting and blinds. *Lighting Research and Technology*, *35*(3), 243–260.

Rushing, A. S., Kneifel, J. D., & Lippiatt, B. C. (2013). *Energy price indices and discount factors for life-cycle cost analysis – 2013. Annual supplement to NIST Handbook 135 and NBS special publication 709*. National Institute of Standards and Technology. U.S. Department of Commerce.

Santos, A. J. (2011). *Desenvolvimento de um método para a caracterização dinâmica da iluminação natural nos edifícios aplicável a climas mediterrânicos*. IST/LNEC.

Santos, A. J. (2014). *A Iluminação Natural nos Edifícios. Uma perspetiva no âmbito do conforto ambiental e da eficiência energética*. Informação Técnica de Edifícios N.º 57 (ITE 57).

Wagiman, K. R., Abdullah, M. N., Hassan, M. Y., Radzi, N. H. M., Bakar, A. H. A., & Kwang, T. C. (2020). Lighting system control techniques in commercial buildings : Current trends and future directions. *Journal of Building Engineering*, *31*(September 2019), 101342. https://doi.org/10.1016/j.jobe.2020.101342

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