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Market-Oriented Cost-Effectiveness and Energy Analysis of Windows in Portugal

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Abstract: Glazed systems in buildings can account for a significant part of overall energy consumption. The unfavorable relationship between energy savings and the increased cost of energy-efficient windows is often the main drawback cited by customers to justify its non-acquisition. of glazed windows. This study addresses the relationship between the investment costs in windows and their energy performance and associated costs. Seventeen window manufacturers were contacted. This survey studied the state-of-the-art and the most-used windows in terms of energy efficiency and cost. Calumen and Guardian Configurator software were used to perform this assessment. Additionally, SEnergEd software was used to simulate the energy performance and compute the equivalent annual cost for the entire life cycle of buildings. Besides the economic benefits, the impact of the energy performance of the windows on the energy performance of the building was also studied. In terms of energy, the most efficient glazing system was two windows per span, resulting in a combined solar factor of 0.43 and a 0.55 W/(m^2·K) heat-transfer coefficient. On the other hand, one window per span, with a solar factor of 0.79 and a 3.05 W/(m^2 K) heat-transfer coefficient is the most cost-efficient to be used in Portugal.

Keywords: glazed systems; windows; energy performance; life cycle cost; equivalent annual cost; nZEB; energy needs; building's dynamic simulation

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1. Introduction

Environmental sustainability and energy efficiency are now well-anchored criteria in the building sector. Over the past few years, there has been an awareness of the theme of sustainable construction and rationalization of energy consumption by designers and architects, as well as by the society in general.

With the signing of the Kyoto Protocol (1997), each signatory state pledged to take all necessary measures to reduce the production of the gases responsible for the increase in the greenhouse effect that contributes to global warming. In order to comply with the assumptions enshrined in this Protocol, the European Union, whose buildings are responsible for spending more than 40% of total energy [1], decided to, as one of its main objectives, improve the energy efficiency of buildings. To this end, it imposed environmental protection requirements on its Member States in its policies and actions (Directive 2002/91/EC), updated in 2018 Energy Performance of Buildings Directive (2018/844/EU) [2]. Recently, in 2020, a wave of renovations [3] of public and private buildings, as part of the European Green Deal [4] that included new rules on the smart readiness of buildings (published alongside the renovation wave strategy in October 2020), was also announced.

In compliance with such energy performance policies, Portugal has transposed this commitment into national legislation through the publication of two Decree-Laws, DL 79/2006 and DL 80/2006, updated in 2013 by DL 118/2013 of 20 August [5]. This diploma revised the regulations on the thermal and energy performance of buildings. Herein, in a single diploma was embodied the Energy Certification System for Buildings (SCE) [5], the Energy Performance Regulation for Residential Buildings (REH) [6] and the Energy Performance Regulation for Commercial and Service Buildings (RECS) [7]. These diplomas also included the concept of nZEB (near-zero energy building), which was supposed to become the standard for the new buildings in 2020.

As a means to comply with the legislation, the improvement of the overall energy performance of a new or existing building starts with the adoption of measures, including a great number of variables. In the case of energy retrofitting, for example, the building envelope requires constructive solutions for the opaque and transparent elements. While the opaque envelope may change its composition ("layer order" and thickness [8]), glazing surfaces are often an obstacle when it comes to minimizing thermal transfers. These elements are the most vulnerable points on façades with the greatest heat losses during the winter (between 25 and 30%) and greatest solar gains in the summer. In wintertime, heat losses can be compensated with solar gains during the daytime, depending on the availability of sun and on the glazing systems (optical characteristics, geometry and orientation, and existence or not of shading devices) [9].

As a corollary choice of glazed openings and performance, the concept of nearly-zero energy building (nZEB) is based on the principles of space comfort associated with energy-saving and the sustainability of buildings. A poorly designed thermal envelope affects heating and cooling needs, and an increase in energy consumption is inevitable to achieve the desired thermal-comfort conditions. Therefore, it is essential to know how the transparent elements of the envelope contribute to the overall performance of buildings.

Each building opening can be composed of one or more glazed windows, internal protection (curtain, blackouts, etc.), and exterior solar protection (roller blinds, shutters, etc.). As suggested by Steen Englund et al. [10], in their field and simulation study in a Swedish school, in case of building renovation, windows can also be part of the solution. But the significance of such elements has even more importance in the case of constructive elements of poor quality, e.g., poor-quality windows.

Table 1 presents a summary of an intensive literature review of studies focused on measures to improve the performance of glazing systems. As evidenced, different authors adopted different methods to perform such studies, namely: life-cycle cost (LCC), life-cycle assessment (LCA), energy analysis or thermal comfort. The most common case studies are of the residential typology, including apartments and dwellings. This review considered also the type of parameters that were varied in each study (type of parametric analysis): type of window, window-to-wall ratio (WWR) and shading. As shown, a significant majority focused on window type. In this study, authors characterize this market in the Portuguese context.

Table 1. Studies about measures to improve the performance of glazing systems.

References	Buildings						Methodology				Measures			Location/Climate
	Residential		Service											
	Apartment	Dwelling	Commercial	School	Office	Healthcare	LCC	LCA	Energy Analysis	Thermal Comfort	Window Type	WWR	Shading	
[11]						•		•	•	•		•		Naples, Italy
[12]	•						•				•			Lecce, Italy
[13]					•		•		•	•	•		•	Naples, Italy
[14]		•							•		•	•	•	4 zones, Mediterranean
[15]		•					•		•		•			Helsinki, Finland
[16]		•					•	•			•		•	Helsinki, Finland
[17]			•						•		•			Singapore
[18]					•		•	•			•			3 zones, Mediterranean
[19]				•			•	•	•		•		•	Xanthi, Greece
[20]		•					•		•		•			14 zones, Europe
[21]		•					•				•			Albuquerque, USA
[22]					•		•				•			Italy
[23]	•						•				•			2 zones, Italy
[24]		•					•	•	•				•	Netherlands
[25]				•				•	•		•		•	Turin, Italy
[26]	•	•					•						•	2 zones, Greece
[27]	•						•	•	•				•	Greece
[28]	•								•	•		•	•	227 zones, IWEC 3012 zones, IWEC2
Studies for the climate of Portugal														
[29]	•						•	•	•		•			3 zones
[30]		•					•		•		•			Porto
[31]	•						•				•			Lisbon
[32]		•			•		•	•	•		•			Coimbra
[33]				•					•	•			•	Porto

In Portugal, more than 70% of the residential building stock still incorporates simple glass windows, as shown in Table 2. This data was assessed in 2011 in a survey about the energy consumption in the domestic sector [34], shows the type of windows that are most applicable to the different facades of residential buildings in Portugal. However, nowadays glazing systems may be composed of two windows or even three and are used to reduce environmental noise and improve the thermal performance of the building.

Table 2. Typology of glazed windows by facade orientation—Portugal, 2010, adapted from [34]. Area—average area per household orientation [m^2].

Type of Windows	South-Oriented		East-Oriented		West-Oriented	
	Households	Area	Households	Area	Households	Area
Simple glazed	74.4%	4.5	71.5%	4.5	71.4	4.3
Double glazed without thermal cut	18.6%	6.3	22.5%	6.5	22.6	6.0
Double glazed with thermal cut	7.0%	7.2	6.0%	5.5	6.0	5.3

Within this context, authors assumed the importance of systematizing the type of windows used in Portugal used in the construction of energy-efficient buildings (or even nZEBs). It is noteworthy that in Portugal, there are still no nZEBs [35], therefore, this study focused on the most common building stock, for which opaque construction solutions of very good thermal quality were assumed.

The updated version of the SCE [5], DL 194/2015 [36], and Ordinance 379-A/2015 [37], led to a revision of the window requirements in Portugal, briefly synthesized in Table 3.

Table 3. Prescriptive window requirements defined by Ordinance 379-A/2015 [37], (since 15 December 2015). Maximum value of thermal transmission coefficient ($U_{w,\max}$) and of solar factor ($g_{\perp,\max}$) of glazed spans.

$U_{w,\max}$ [W/(m^2.°C)]	(Winter) Climate Zone		
	I1	I2	I3
Glazed spans (doors and windows) (U_w)	2.80	2.40	2.20
$g_{\perp,\max}$	(Summer) Climate Zone		
(class of thermal inertia)	V1	V2	V3
weak	0.15	0.10	0.10
average	0.56	0.56	0.50
strong	0.56	0.56	0.50

In summary, the objective of this study is twofold: (i) to characterize the windows usually installed in the Portuguese building stock, both in terms of energy quality and cost of acquisition; (ii) and to evaluate the relationship between these two parameters.

Therefore, the present study is divided into two parts. The first part addresses the characterization of the Portuguese market for windows. A wide range of manufacturers was inquired concerning windows' price and characteristics typically used in the Portuguese market. The standardization of windows' characteristics led to eight categories of windows. The second part focuses on researching the best performance windows for buildings in terms of economics and energy. The concept of optimal cost considers the lowest expenses related to the windows during the entire life of a building (initial investment, maintenance, heating ventilation and air-conditioning (HVAC) systems' energy consumed due to the existence of glazing, and end-of-life costs). While for energy aspects, minimal energy consumption through the useful life of a building with a specific window type suggests the optimal energy solution. All these aspects used software and calculation methods to perform such analysis as presented in Section 2: Methods. Then, case studies are presented, contextualized and characterized in Section 3. This section is followed by Section 4: Results, wherein the relation between the cost of acquisition of the windows with the reduction in energy costs allowed the identification of the optimum point of economic profitability for windows. The main results are then summarized in Section 5.

2. Methods

2.1. Framework

The present study looked for the best window solution for a representative building stock. Four main building typologies were considered: (i) residential buildings (an apartment and a detached house), (ii) service buildings with permanent occupancy (a private clinic with hospitalization), (iii) service buildings with intermittent occupancy (a private high school and a bank branch) and (iv) commercial buildings (a medium-sized supermarket). The considered buildings were then simulated in three distinct sites, representative of the Portuguese climate.

2.2. Windows in the Portuguese Market

For the purpose of identifying the optimum point of economic profitability for windows in Portugal, authors started by asking information regarding a wide range of windows manufacturers, including: (i) the most frequently installed size of windows (ii) price and (iii) energy class categories, from very bad to excellent. Besides the identification of the typically commercialized windows' characteristics and prices, companies were also asked to provide windows datasheets and group them into a six-point energy-quality-scale, in detail: very poor, poor, medium, good, very good and excellent. All datasheets referred to the same type of windows, a double layer with 1.30 m and 1.10 m of width and height, respectively, which corresponds to an area of 1.43 m^2 (the current window size most used in Portugal).

From the collected datasheets, 17 companies provided, in total, 81 quotations. However, some of the manufacturers did not provide all of the requested window-scale qualities; otherwise, the total windows evaluated would have been 108. From the 81 windows solutions, 70 are made of aluminum (with and without thermal cut), 8 of PVC, and 3 of wood. The window opening types surveyed included 72 casement windows and 9 sliding windows.

The analyzed datasheets allowed the characterization of windows' properties, namely, the solar factor ($g_{\perp}$) and the heat-transfer coefficient of the window (U_w). These values were calculated using Calumen and Guardian Configurator. Both software adopted EN 410 [38] and EN 673 [39] to calculate the windows' technical characteristics: light transmission, solar factor or the heat transfer coefficient for any type of glass.

As stated, not only the characteristics of the windows were surveyed but also their prices—the datasheets also included the installation cost of the glazing systems. However, prices on datasheets were relative to the area of 1.43 m^2, as previously mentioned. If a window has an area of less than 0.5 m^2, its cost is the same as if it were 0.5 m^2.

As the suggested classification for each type of window differed substantially from manufacturer to manufacturer, it was necessary to revise the energy classification according to the components assembled to shape each window. The categorization process required weighting two parameters, the window heat-transfer coefficient (U_W) and the solar factor (g), in the single indicator expressed by Equation (1).

$$R = 0.6\, R_{U_w} + 0.4\, R_g \quad (1)$$

R—window energy rating [-], R_{U_W}—rating of the window heat-transfer coefficient [-] and R_g—Rating of the window solar factor [-].

Both ratings, R_{U_W} and R_g, are normalized against reference values of the Portuguese regulation: $U_{w,\max}$ = 2.2 W/(m^2·K) and $g_{\perp,\max}$ = 0.5, using Equation (2).

$$R_{U_w} = \frac{U_W}{U_{W,\max}},\ \ R_g = \frac{g}{g_{,\max}} \tag{2}$$

U_W—heat transfer coefficient of the window [W/(m^2·K)] and g—solar factor of the window [-].

The window energy rating (R) was then used to reclassify all the windows' energy ratings, as presented in Table 4.

Table 4. Windows' energy ratings.

Window Energy Ratings	**Parameter *R***
Class H	$R > 1.75$
Class G	$1.50 < R \leq 1.75$
Class F	$1.25 < R \leq 1.50$
Class E	$1.00 < R \leq 1.25$
Class D	$0.75 < R \leq 1.00$
Class C	$0.50 < R \leq 0.75$
Class B	$0.25 < R \leq 0.50$
Class A	$R \leq 0.25$

2.3. Window Energy Performance and Equivalent Annual Cost

To obtain the most efficient type of window in terms of energy needs for climatization and for economic value, the SEnergEd software was used [40,41]. For this, different buildings with changes in their glazed windows solutions were simulated.

SEnergEd was developed to combine the dynamic simulation of a building with an economic analysis of its entire life, considering all the associated costs. Thermal performance is calculated based on the ISO 13790 [42] dynamic model, 5R1C (5 thermal resistances and a thermal capacitance). Dynamic hourly calculations were used to compute other energy needs. It was previously validated by Claro [43], who compared simulation results with the measured energy consumption of a high school over an entire year. Further details can be found in the studies of Raimundo [8,41].

Buildings are predesigned according to the typology of use (residential, commercial and services) that may have a great impact on energy needs. On the one hand, energy needs depend on use (time and intensity), which, in turn, differs very much from typology to typology. On the other hand, a building's physical characteristics associated with such typologies, the geometry and orientation of the building, its location and constructive solutions (opaque and transparent) are also key aspects of the calculation of energy needs. Considering the building envelope, windows contribute to such differences, and the present work evaluates the impact of using different classes of windows. In other words, the need for a change in window solution was assessed, excluding the type of energy systems (which was constant in all simulations). All values were standardized by dividing this value per window area. The energy needs of climatization due to windows were used to achieve the optimal window solution for each building.

SEnergEd software predicts building energy needs by function (heating, cooling, ventilation, lighting) and not by construction elements. Then, the energy needs for climatization due to the existence of glazing are obtained using the expression (3).

$$Q_W = \frac{Q_{WG} - Q_{NG}}{A_G} \tag{3}$$

Q_W—energy needs due to the existence of windows [kWh/(m^2·year)]; A_G—glazing area [m^2]; Q_{WG}—building energy needs [kWh/year]; Q_{NG}—energy needs of the same building but without glazing [kWh/year].

To identify the optimal point of economic profitability of windows, the equivalent annual cost (*EAC*) of the building was used. This indicator represents the effective economic effort that the holder has to support each year for the use of the building, being equivalent to all expenses, revenues and tax savings related to it [8]. The expenses include initial investment, end-of-life costs, major repairs, annual tax due to building ownership and the annual costs of maintenance, energy consumption and other costs. The solution with lower *EAC* corresponded to the optimum situation from an economic point-of-view in the climate of Portugal.

In the present study, SEnergEd software was used to compute the *EAC* of each building under several Portuguese climates. This tool performs an economic assessment of the total expenditures of a building through its life cycle given its thermal and energy performance. The total expenses in the initial investment, energy consumption and residual value led to the estimation of the building *EAC* throughout its entire life cycle. This economic analysis is based on the concept of *EAC*, which is calculated using Equation (4).

$$EAC = -NPV \cdot \frac{r\,(1+r)^{n}}{(1+r)^{n}-1} \quad (4)$$

EAC—building equivalent annual cost [€/year]; *NPV*—building net present value [€]; *r*—real interest rate [1/year]; *n*—lifetime [years].

The *NPV* is calculated following the approach defined in the European Regulation of 2012 [44], in EN 15459:2007 [45], and presented in the study of Raimundo et al. [8]. *NPV* considers the investments, the residual value of the building and the cash flow each year. Therefore, any revenue from selling energy or renting space, any paying and saving of taxes and any costs are considered.

The Portuguese fiscal context has significant taxing discounts that are critical for the economic analysis of the study. The application of taxes depends strongly on the building's use and the tax-framework of the holder, which must be included in the building expenditures. For an economic assessment, some assumptions must be done. Summarily, taxes included in the methodology of this study were: (i) annual taxes for owning the buildings (0.4%/year), (ii) value-added taxes (VATs), 23%, for any transaction and (iii) tax savings for professional activities according to revenues (individuals are not included). The annual taxes due to holder/ownership depend on the type of use and building, and not the owner, while VAT recovery depends on the type of holder/owner.

The adopted period for an economic analysis depends on the lifetime (*n*) of buildings, which for a Portuguese scenario can be considered 50 years. During this period, interest rates were assumed to be constant. Even though, in similar studies, these rates ranged between 0 to 15%, depending on the type of commodity (average prices, energy tariffs, or discount rates), for the present work, the interest rate considered was 3%/year [8,32], which is in concordance with the European Union economic context.

Maintenance costs were also considered in the analysis: 1%/year was assumed relative to the initial construction cost, and 4%/year of the total costs on heating, ventilation and air-conditioning (HVAC); domestic hot water; renewables; lighting; and other appliances). Replacement of the energy systems was considered after 25 years.

Finally, given the performance of the HVAC equipment, the annual energy consumption for the building was calculated according to thermal needs. Considering the energy tariffs (electricity and natural gas) according to the consumer type (domestic or commercial and services), the energy consumption was converted into annual expenditure.

Given the economic aspects of the analysis, the value of EAC_W (equivalent annual cost of windows per glazing area) was used to determine the most economic window, which corresponds to the minimum value estimated. Since this *EAC* value is related to all expenditures throughout the lifetime of the building, including the initial investments on the building envelope, maintenance and energy costs, *EAC* for the building without windows (EAC_{NG}—equivalent annual cost of the building without glazing) was removed from the total EAC_{WG} (equivalent annual cost of the building with glazing), which includes the total cost of the building with glazing, giving the analysis indicator only the costs concerning windows. This value was divided by the glazing area of the building in order to standardize results and compare values from different buildings, EAC_W. In this way, any economic cost or saving from the building envelope is removed from the analysis, allowing comparable results.

Since this software allows the estimation of the building EAC and not one specifically for the windows, further calculations are required, as suggested in Equation (5), which defines the economic indicator that was used to determine the most economic window.

$$EAC_W = \frac{EAC_{WG} - EAC_{NG}}{A_G} \tag{5}$$

EAC_W—equivalent annual cost of windows per glazing area [€/(m^2·year)]; A_G—glazing area [m^2]; EAC_{WG}—equivalent annual cost of the building with glazing [€/year]; EAC_{NG}—equivalent annual cost of the building without glazing [€/year].

The above-mentioned approach was repeated for several buildings in three Portuguese climates for each window class, presented in the next section.

3. Buildings, Windows, Climate, and Air-Conditioning Systems

3.1. Buildings

This study included four main building typologies, covering a broader and representative building stock of the Portuguese national context: residential, service with permanent occupancy, service with intermittent occupancy and commercial buildings. As different operations could induce changes in buildings of the same category, six different building types were considered in total, namely:

1. Residential:
    - A second-floor apartment in a residential block,
    - An individual three-story house with a private garden,
2. Services with permanent occupancy:
    - A private clinic in a two-story building with permanent occupancy,
3. Services with intermittent occupancy:
    - A private high school as a set of seven buildings with intermittent occupancy (only daytime),
    - A bank branch (only daytime occupancy),
4. Commercial:
    - A medium-sized supermarket (daytime and part of night occupancy).

Further details of the building types can be found in Raimundo et al. [8]. A summary of the main characteristics of each building is presented in Table 5, and a synthesis of each building operation scheduling is presented in Table 6.

Regard the thermal properties of the envelope, a homemade spreadsheet was used to calculate those parameters following the methodology proposed in ISO 6946 [46], with the database of the Portuguese system of building energy certification [5]. To determine the prices of the different construction solutions, an online tool was used, Cype Price Generator [47]. It is an online database that allows the obtention of the real construction prices adjusted to the Portuguese market.

Table 5. Summary of the characteristics of the six buildings considered.

Building	Apartment	Detached House	Private Clinic	Private High School	Bank Branch	Supermarket
Occupancy [person]	4	4	151	1100	12	194
Floors [–]	1	3	2	4	1	1
A_{cl} [m^2]	109.4	167.1	926.7	11,246.0	111.4	1035.3
Vol [m^3]	286.6	494.6	3447.3	43,184.6	289.5	3727.1
A_{opc} [m^2]	58.6	343.4	743.4	22,703.8	181.0	2507.0
A_{glz} [m^2]	21.3	49.7	192.8	2975.3	37.20	96.6
AR [m^{-1}]	0.28	0.79	0.27	0.59	0.75	0.70
WWR [-]	0.27	0.13	0.21	0.12	0.17	0.04

Occupancy—maximum number of occupants, N_f—number of floors, A_{cl}—air-conditioned area, *Vol*—air-conditioned volume, A_{opc}—opaque area of the building envelope, A_{glz}—glazed area, *AR*—aspect ratio = $(A_{opc} + A_{glz})/Vol$, *WWR*—window-to-wall ratio = $A_{glz}/(A_{opc} + A_{glz})$.

Table 6. Synthesis of operation and occupancy schedule for each building.

	Building Typology	Occupancy Schedule	Notes
Residential buildings	**Apartment** **Detached house**	Daily (1 person), From 18 h to 8 h (4 people); Weekends, full occupancy	Unoccupied during the first 15 days of August
Services	**Private clinic**	Continuous	All year long, more intense occupancy during the daytime on weekdays and Saturdays
	Private high school	Weekdays, 9 a.m. to 7 p.m.	Scholar calendar: 100% during school periods 50% during the 1st period of exams (15–30 June) 25% during the 2nd period of exams (1–15 July) 25% during the admission phase (16–31 July). Closed on school holidays (the first 15 days of April, 1–31 August, and the last 15 days in December)
	Bank branch	Weekdays 9 a.m. to 5 p.m.	All year long
Commercial	**Supermarket**	Daily, 8 a.m. to 10 p.m.	More intense occupancy on weekends

3.2. Windows

A complete description of the most commercialized windows in Portugal and their energy classification, developed by the authors, is in Table 7.

According to the proposed classification in this study, from the 81 budget windows, 6 belong in class H, 4 in G, 19 in F, 23 in E, 16 in D and 13 in C, which leads to the conclusion that none of the manufacturers' windows were of classes A or B, thus requiring a solution to have windows of classes A and B. Combining two windows, one interior and one exterior, instead of only one, classes A and B were composed of two windows selected from the previous classes (Table 7).

It is important to note that this study considered that glazed elements did not have internal protection. Only external shutters with 45 mm horizontal plastic rulers were considered. This is a frequently used external occlusion solution in Portugal. Their costs were added to the price of each glazed element throughout the simulations.

Table 7. Commercialized windows in Portugal.

Window Description (Glass Sheets from Exterior to Interior)	Class
Aluminum frame without thermal cut and with simple colorless glass	H
Aluminum frame without thermal cut and with double glass (colorless + air + colorless)	G
Aluminum frame with thermal cut (or PVC or wood) and double glass (colorless + air + colorless)	F
Aluminum frame with thermal cut (or PVC or wood) and double glazed (colored + air + colorless) or (colorless with reflective film + air + colorless) or (colorless reflective + air + colorless)	E
Aluminum frame with thermal cut (or PVC or wood) and double glass (colored reflective + argon + colorless "thermal")	D
Aluminum frame with thermal cut (or PVC or wood) and triple glass (colored reflective + argon + colorless "thermal" + argon + colorless)	C
Two independent windows per span: (two of class E) or (one of F and one of D) or (one of G and one of C)	B
Two independent windows per span: one of class D and one of class C	A

Given the window energy rating, characteristics and prices, the respective average ($\bar{x}$) and standard deviation (σ) values of the windows typically commercialized in Portugal, a synthesis is presented in Table 8. The prices are based on the received quotations, expressed per square meter, including the cost of the window and of installation. To obtain the cost of the glazing, the expenses with acquisition and installation of the occlusion devices (60.46 €/m^2, without *VAT*) should be added.

Table 8. Characterization of windows typically commercialized in the Portuguese market. Costs without *VAT*.

Energy Rating		H	G	F	E	D	C	B	A
U_W	$\bar{x}$	4.723	3.788	3.053	2.407	1.994	1.225	0.554	0.477
[W/(m^2·K)]	σ	0.064	0.053	0.266	0.409	0.242	0.207	0.094	0.041
g	$\bar{x}$	0.877	0.837	0.786	0.713	0.471	0.440	0.427	0.114
[-]	σ	0.005	0.022	0.011	0.124	0.091	0.079	0.017	0.005
Price	$\bar{x}$	101.07	117.58	124.52	172.35	196.23	240.89	333.54	422.70
[€/m^2]	σ	54.31	25.45	43.57	54.08	40.98	78.27	83.01	87.79
R		1.99	1.70	1.46	1.23	0.92	0.69	0.49	0.22

These parameters were used as input variables in the simulations to study the optimal solution of windows in Portugal in terms of economics and energy.

3.3. Air-Conditioning Systems

The indoor environment is ensured by an HVAC (heating, ventilation and air conditioning) system, composed of fans with 70% efficiency and a chiller/heat pump using a compression cycle with an efficiency for heating *SCOP* = 4.30 and for cooling *SEER* = 5.85, class A+ [48].

As for air-conditioning, setpoints for indoor air temperature between 21 °C and 24 °C were established, and the HVAC system was on whenever the building is occupied. For the Portuguese climate, a chiller/heat pump system in heating mode has reasonable efficiencies; however, the same does not apply to colder climates. Other energy systems could be described (as lighting or domestic hot water (DHW)), but as these do not impact the final results, only the air-conditioning systems are presented.

Both the price of electricity and natural gas, excluding VAT, were based on data from Eurostat from the second semester of 2020 [49], respectively, for the residential buildings (0.174 €/kWh and 0.078 €/kWh), and for service and commercial buildings (0.111 €/kWh and 0.059 €/kWh).

3.4. Portuguese Climate

The Portuguese regulation for building energy certification [5] establishes three winter climates (I1, I2 and I3) and three summer climates (V1, V2 and V3), according to the heating degree days (*HDD*), based on 18 °C, and the mean outdoor temperatures (T_{ext}), instead of cooling degree days (*CDD*), based on 24 °C. Though the three winter areas combined with the three summer zones allowed a combination of nine possible climate zones [5,8,50], authors opted to represent the Portuguese weather, through the simulation of the buildings in three climatic zones, namely: (i) mild climates I1–V1 (Funchal at 415 m, *HDD* = 793 °C days/year, T_{ext} = 20.2 °C, *CDD* = 16 °C days/year); (ii) intermediate climates I2–V2 (Ansião at 361 m, *HDD* = 1562 °C days/year, T_{ext} = 21.2 °C, *CDD* = 112 °C days/year); and (iii) intense climates I3–V3 (Mirandela at 600 m, *HDD* = 2085 °C days/year, T_{ext} = 22.1 °C, *CDD* = 218 °C days/year).

4. Results

4.1. Energy Needs for Air-Conditioning Due to Windows

The energy needs for climatization due to windows [kWh m^{-2} $year^{-1}$], whose values are expressed per m^2 of glazing, for each of the six building types, according to the eight window-energy classes previously defined, was simulated for each one of the three climate zones, as shown in Figure 1.

Figure 1 deserves some observations in particular: (i) when the *y* axis equals "0", this corresponds to the "No windows" scenario (no energy gains, no energy losses by glazing); (ii) every time a point is below "0", it means glazing is leading to energy savings; (iii) the fact that, for each building type, the energy class of windows is presented along with the climate zone, allows the investigation of where the energy classes of windows could have a higher or lower influence on building energy consumption.

Another general comment that could be addressed in Figure 1 concerns the fact that, for some building typologies, having windows may not necessarily contribute to a reduction in energy needs, as for the buildings with all points above the "No windows" reference line. Also, as observed in five out of the six pictures that comprise Figure 1, it is not evident that the best window energy class (A) actually performs the best, i.e., leading to lower energy needs (including both cooling and heating). In the case of the residential typology, for example, windows of class B show better performance in all climate zones. This comes from the balance between the heat gains and losses due to the U_W and g. For class A, the g is so low that it does not compensate for the positive contribution of a low U_W. Nonetheless, the economic difference between class C and class B is only justifiable in an apartment or detached house in zone I3–V3, the more intense climate. The analysis of the results also demonstrates that the decision of window solutions in the residential buildings and in the clinic have a higher impact on energy needs with the increase in intense weather. This indicates that these buildings may depend more on outdoor conditions, since differences between the results in several locations are much more noticeable than in the private high school, bank branch or supermarket.

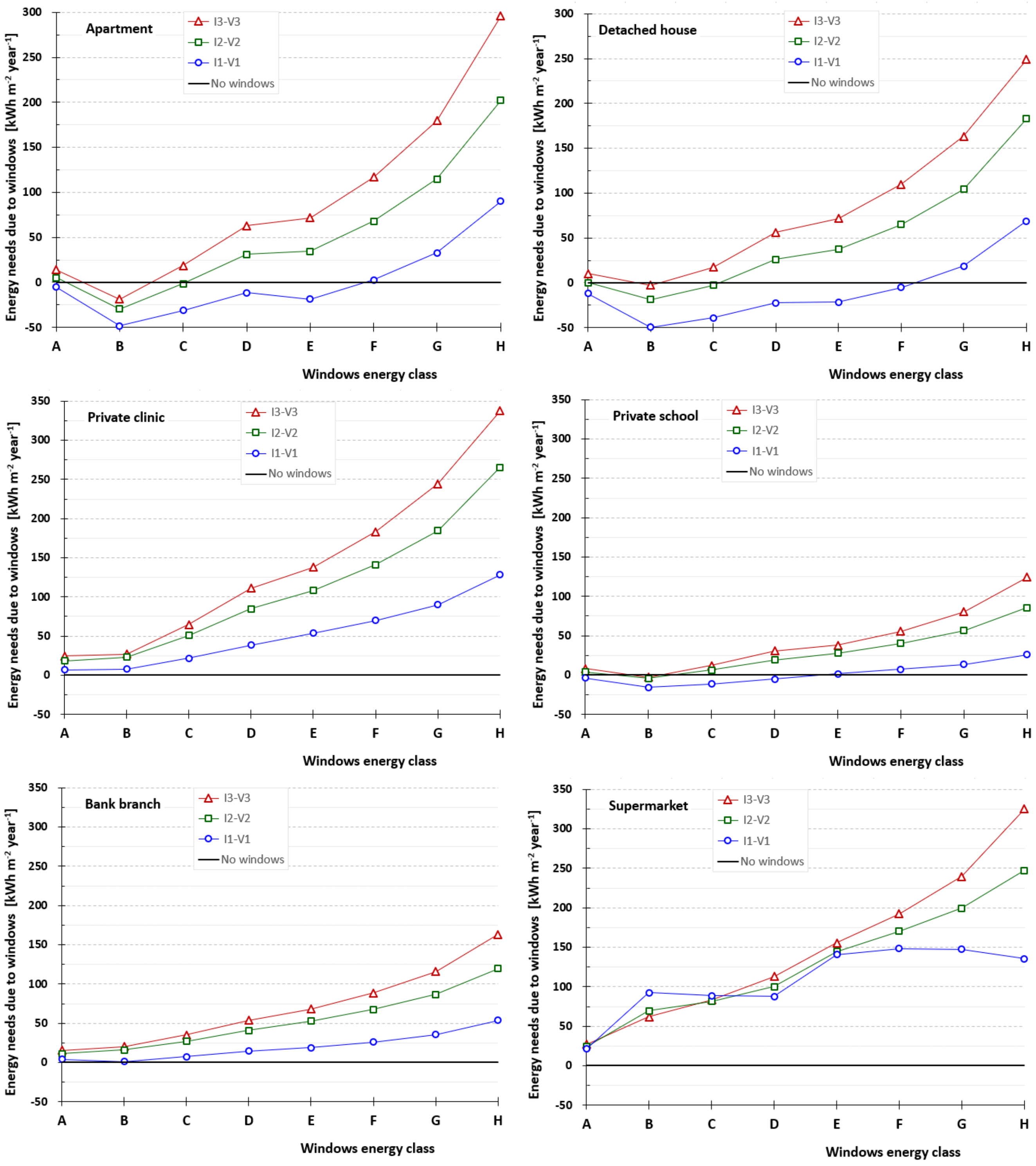

Figure 1. Energy needs for air-conditioning due to windows for each building type, varying according to each climate zone (values per m^2 of glazed area of external envelope).

In Figure 2, the energy needs for cooling and heating due to windows, for each building, in all climate zones and windows type, are shown separately. These results relate significantly with the building type occupancy (Table 5). For example, both the apartment, the detached house (*Dwelling* in Figure 2) and the clinic present more dispersed data for heating than cooling needs—the residential typology has higher occupancy during nighttime and assumes an unoccupied vacation period during summertime. Nonetheless, as appointed by the "x" in the boxplot, the averaged energy needs are practically the same for the apartment and for the detached house; both the average and median (middle horizontal line of the boxplot) values for heating are lower than for cooling.

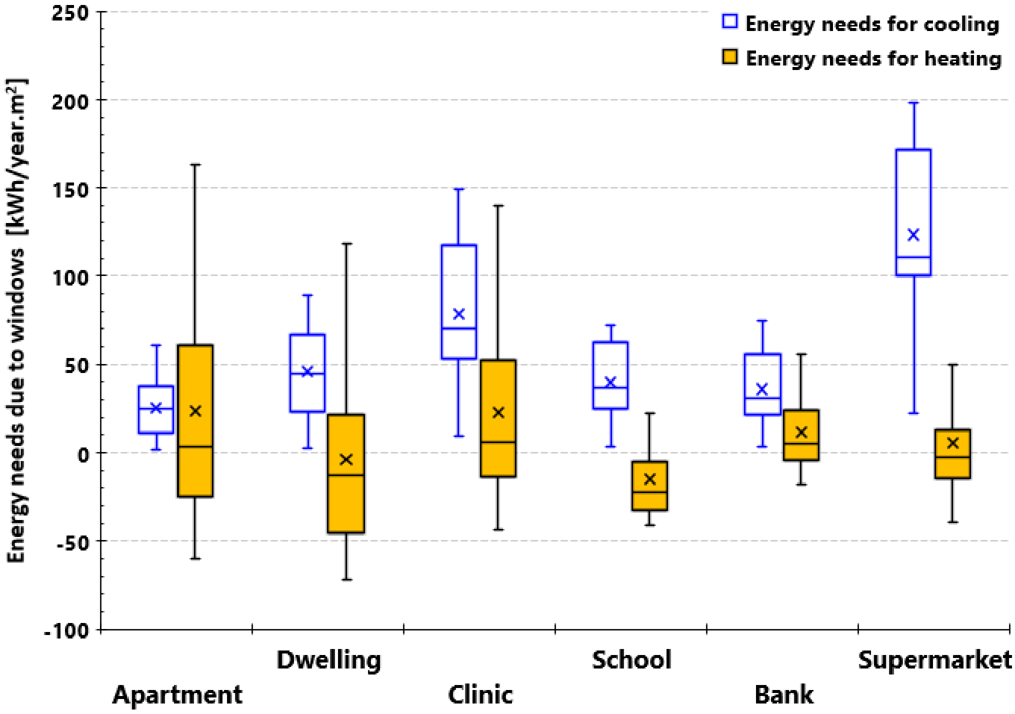

Figure 2. Energy needs for heating and for cooling due to windows (values per m^2 of glazed area of external envelope). Values for each building include all climate zones and all windows type.

With the clear exception of the apartment, all other building types show higher cooling than heating needs. The reason is that the glazing systems are more shaded in the apartment than in the other buildings (in the apartment, the glazing areas are shaded by outdoor balconies on the upper floor). Such energy needs are particularly expressive in the case of the supermarket—because it works continuously during the entire year, as it has significant internal load gains, e.g., big cold storage equipment/areas that release heat inside this space. On the other hand, it is important note that such energy needs are expressed in the same unit: m^2 of glazed area of external envelope. This means that, for example, in the case of supermarkets, the glazed area should be reduced to a minimum, and, in the case of the private clinic, each m^2 of glazing should also be very well thought out at the design stage of such building type. In the case of the private high school, its utilization profile led to a certain compromise between the cooling and heating needs due to glazing, hence its existence has a low impact on energy needs for climatization.

4.2. Windows Equivalent Annual Cost

Just like for the energy needs, in Figure 3 is shown the windows equivalent annual cost (EAC_W) (values per m^2 of glazed area of external envelope), according to the eight windows energy classes, for the six buildings and the three climate zones considered.

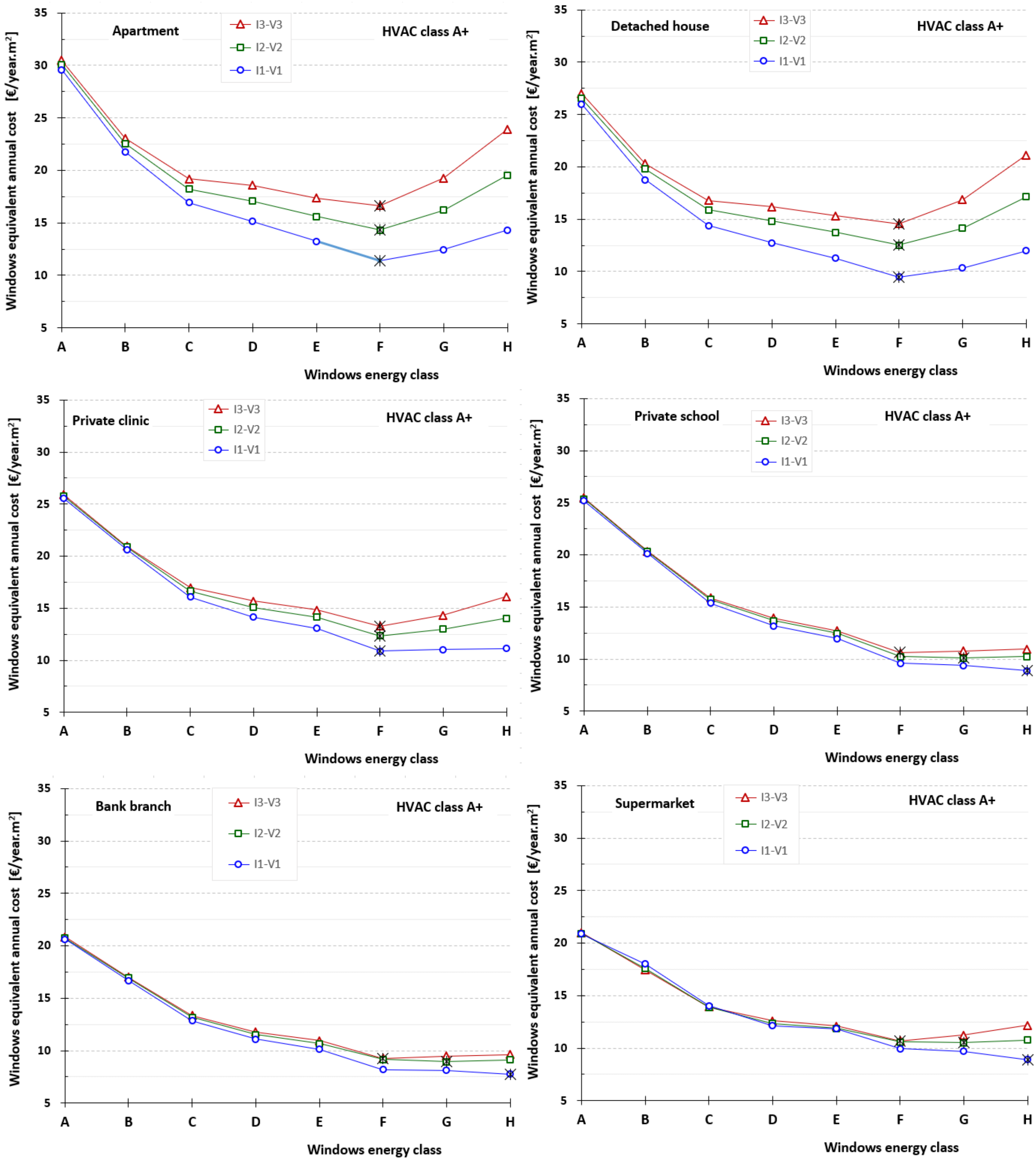

Figure 3. Windows equivalent annual cost (EAC_w), for each building type, varying according to each climate zone (values per m^2 of glazed area of external envelope).

From an economic perspective, the best solution is the one with the lowest *EAC*, corresponding to the optimum situation for that climate zone, which is signaled with a "*X*" in Figure 3. As clearly evidenced by the majority of the graphs, in any circumstance windows of class F are the optimum investment.

Some observations are due in Figure 3:

- In the case of the residential buildings, whenever these are located, the best window solution is "class F"—aluminum frame with thermal cut (or PVC or wood) and double glass (colorless + air + colorless), Table 7. The same result was obtained for the private clinic.

- For residential buildings and the private clinic, a parabolic trend is evident, meaning that the costs of the optimal window are found in the middle energy classes, as the "best" and "worst" classes showed significantly increased costs. For the remaining buildings, this trend is not clear. The trend is more intense with increases in the severity of the climate.
- In the case of the private high school, the bank branch and the supermarket, the best window solution changes according to the climate zone where these buildings are located.
- For the buildings previously mentioned, if these are located in the mild zone, the worst window—H (aluminum frame without thermal cut and with simple colorless glass, Table 7)—is, in fact, the best solution in economic terms, even though the differences compared to class F are very small.

A synthesis of the obtained windows equivalent annual cost (EAC_W) for each building type is presented in Figure 4. The "x" presented in each boxplot represents the average value, while the outliers represent the minimum and the maximum, respectively. As evidenced in this graphic, the EAC_W value varies more in the apartment building type, meaning that windows have higher influence in this building type than in the other five types (it also presents the higher average and median values, wherever it is located).

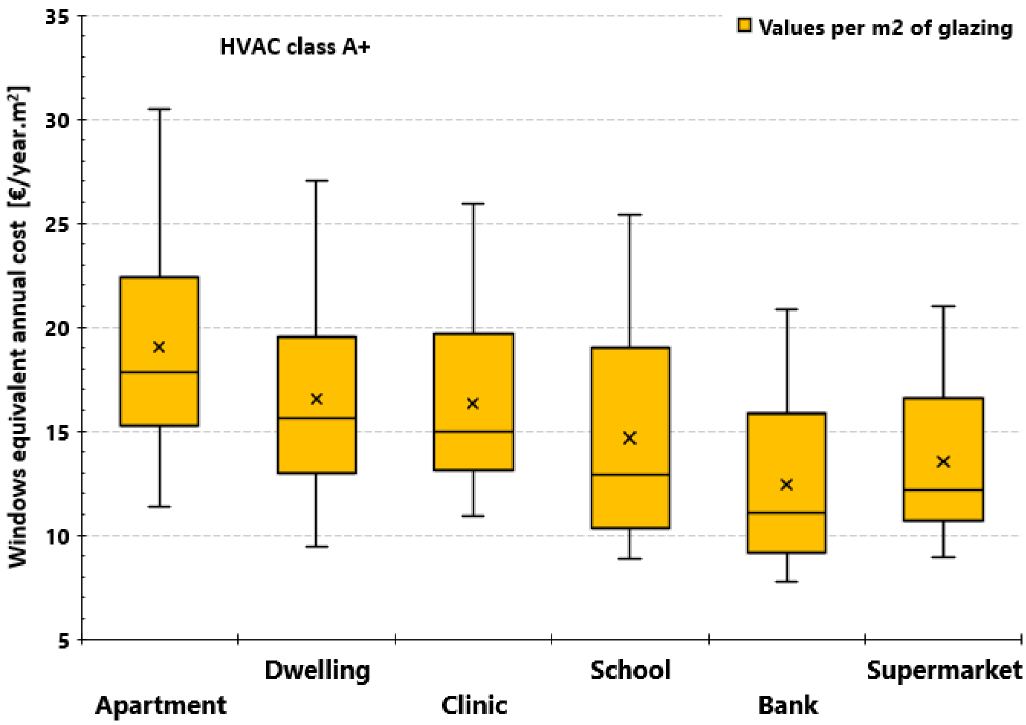

Figure 4. Comparison of windows equivalent annual cost (EAC_W) for all building typologies (values per m^2 of glazed area of external envelope). Values for each building include all climate zones and all windows type.

Figure 4 highlights the costs related to windows for the several typologies. The apartment requires higher costs to have windows, while the bank branch requires the least. In general, buildings with permanent occupancy (apartment, dwelling and clinic) have higher costs for having windows. Buildings with intermittent use (school, bank branch and supermarket) have lower costs due to windows and depend less on the type of window installed.

5. Discussion and Conclusions

The present study addresses two main goals. In the first place, the study aims to characterize the windows installed in Portugal in terms of thermal behavior and costs. For this purpose, manufacturers were contacted regarding the most-used windows in the Portuguese market, where a survey regarding the thermal properties of windows and their installation cost was performed. Then, given the previous characterization, their performance throughout the entire life cycle of the case studies was assessed using SEnergEd software, in terms of energy and economic perspectives. For this purpose, six building typologies were simulated in three climatic zones representative of the Portuguese climate. The methodology adopted included a dynamic simulation of the buildings' thermal and energy performances coupled with an economic analysis for the entire life cycle.

From the surveyed datasheets, 17 companies provided, in total, 81 quotations with several characteristics of glazed windows for six categories of quality. From the results achieved, it was necessary to standardize such information, since companies had different criteria. For that, Calumen and Guardian Configurator software were used, in order to respect a proposed new window rating in compliance with the national regulation. The characterization of the window market in Portugal was rated into eight window types (see Tables 7 and 8).

The results from this characterization were used to simulate several case studies in the three Portuguese climate zones. A summary of the window classes for both approaches are presented in Table 9, highlighting that different solutions must be adopted depending on the approach. From an energy-efficiency perspective, classes A and B are the most efficient. The installation of windows of class B and C in residential buildings promotes energy savings. In the other situations considered, the glazing system is responsible for an increase in energy needs for climatization, which grows with the intensity of the climate and with decreasing window quality. From the economic side, generally, windows of class F have lower costs throughout the entire life cycle of the building. On the other hand, classes A and B are the ones with higher costs. Therefore, results achieved from the two perspectives are significantly different.

Table 9. Summary of the best solution of windows for the Portuguese weather.

Building	**Apartment**			**Detached House**			**Private Clinic**			**Private High School**			**Bank Branch**			**Supermarket**		
Climate Zone	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Energy	B	B	B	B	B	B	A	A	A	B	B	B	B	A	A	A	A	A
Economic	F	F	F	F	F	F	F	F	F	H	G	F	H	G	F	H	G	F

Small differences were registered when comparing the best window classes for the three climate zones. Contrary to the results found in Raimundo et al. [8], wherein climate has a strong impact on the optimal opaque solutions, the optimal window class for energy and economic purposes is less significant. However, more intense climates are always associated with higher costs and energy needs even for a small country like Portugal.

Generally, class F windows [aluminum frame with thermal cut (or PVC or wood) and double glass (colorless + air + colorless)] should be used for economic purposes, but a class B [two independent windows per span: (one from class G and one from C) or (one from class F and one from D) or (two from E)] is the best from an energy perspective. Briefly, it can be stated that it is not possible to find a compromise solution that takes into account both criteria together, the energy-efficiency and the economics.

The results showed that the influence of windows is more dependent on the building type of use and occupation than on geometry and architectural characteristics. No correlation between the most viable window class and the building's aspect ratio (AR) and window-to-wall ratio (WWR) was recorded from this global analysis. Detailed research on the influence of these two parameters will be valuable.

It is important to note that the recommendation of the window class to be applied in Portuguese buildings is mainly applicable to new buildings. In refurbishment, it is applicable to recent buildings (less than 30-years-old—the lifetime considered). For cultural patrimony, careful analysis must be considered, as several restrictions may be imposed by architects.

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Nomenclature

A_G	Glazing area [m^2]
AR	Building aspect ratio
CDD	Cooling Degree Days, based on 24 °C [°C days/year]
COP	"Coefficient of performance" of HVAC system
EAC	Building equivalent annual cost [€/year]
EAC_W	Windows equivalent annual cost per glazing area [€/(m^2 year)]
EAC_{NG}	Equivalent annual cost of the building without glazing [€/year]
EAC_{WG}	Equivalent annual cost of the building with glazing [€/year]
$g_\perp$	Solar factor of the glazed surface
HDD	Heating Degree days, based on 18 °C [°C days/year]
n	Building lifetime [years]
NPV	Building net present value [€]
nZEB	Near zero energy building
Q_W	Energy needs due to the existence of glazing per glazing area [kWh/(m^2 year)]
Q_{NG}	Energy needs for the building without glazing [kWh/year]
Q_{WG}	Energy needs for the building with glazing [kWh/year]
r	Real interest rate [1/year];
R	Window energy rating
R_{U_w}	Rating of the window heat transfer coefficient
R_g	Rating of the window solar factor
U_W	Heat transfer coefficient of the window [W/(m^2 K)]
VAT	Value added tax
WWR	Window-to-wall ratio

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