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Title: Integrated environmental, energy and cost life-cycle analysis of windows: optimal selection of components

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Highlights

- Trade-offs between environmental impacts and costs of windows are presented.
- The influence of climate and orientation on window performance is investigated.
- West-facing windows have higher impacts due to the larger energy needs.
- In warm climates, low solar factor contributes significantly to reduce impacts.
- Window thermal transmittance is key to reduce impacts in cold climates.

Abstract

There is an increasing need for energy-efficient windows; however, these windows can have high embodied impacts and can be costly. This has not been thoroughly analyzed and the literature has mainly focused on the operational performance of windows. It is important to wisely select optimal windows that minimize energy consumption, costs, and environmental impacts throughout their life cycle, considering the influence of window orientation and climate data. This article presents an integrated cost and environmental life-cycle assessment (LCA) of window solutions, combining alternative glazing and framing options. Optimal window solutions were selected using a Pareto bi-objective optimization (costs vs. environmental impacts) for three different European climate regions, considering various window orientations. The influence of each window component (glazing and framing), as well as window properties (thermal transmittance and solar factor) on the overall environmental and cost life-cycle impacts was studied. Pareto optimal window solutions for warm climates highlight low solar factor windows, while for cold climates they highlight low thermal transmittance value. The glazing is the component with the greatest influence on the total environmental impacts (mainly operational). The impacts depend to a very great extent on the thermal transmittance values and solar factors. The life-cycle cost analysis shows that the initial investment in the windows has a high impact on the overall cost, even when a lifespan of 30 years is considered. This article provides insights into and recommendations for the design of windows by addressing different climatic conditions and window orientations.

Keywords

Environmental impacts; Life cycle costing; Windows; Pareto solutions; Building energy consumption

1. Introduction

Windows are essential components of the building envelope since they influence the building's thermal performance and provide lightning and ventilation. Heat transfer through windows can account for a significant share of the overall energy needs of buildings or contribute to the need for additional heating and cooling. However, modern energy-efficient windows are costly and require significant quantities of materials. Thus, proper strategies should be used to wisely select optimal windows that minimize energy consumption, costs, and environmental impacts throughout their life cycle [1].

The thermal transmittance value (U-value) and solar factor (g-value) are the properties with an important role in the energy balance of windows. However, research on the influence of the window properties has mainly focused on the operational energy performance of windows [2], [3], overlooking life-cycle environmental impacts and costs. In addition, much of the current literature on window properties tends to focus on a single element of windows [4], with most authors concentrating on the framing [5]–[8], a few on the glazing [9], [10], and shading [11]–[13]. The rest have studied whole windows rather than addressing the impacts of individual components [14]–[16].

There has been an increasing amount of literature recently on the environmental performance of windows. Much of this literature has paid particular attention to the environmental impacts in the operation phase [17], [18] and very few studies have investigated the embodied impacts of windows [7], [19], while the environmental performance of windows over their complete life cycle (LC) has been overlooked. Several attempts have been made, however, to investigate the economic performance of windows without looking at the environmental performance. Menzies and Wherrett [16] investigated the energy and cost savings that might be achieved in the design and selection of sustainable multi-glazed windows. Jaber and Ajib [20] identified the optimum window type and size to reduce both energy and investment costs for three climate zones (Amman, Aqaba, and Berlin).

Environmental and cost life-cycle assessment can be integrated to explore the most influential window properties (U- and g-value) and components (glass and frames) in terms of the economic and environmental performance and to estimate the environmental and cost benefits of the window solutions [21], [22]. So far, Minne et al. [15] applied an integrated environmental and cost life-cycle analysis to alternative windows for a single-family home in various US climate regions. However, the contribution of individual window components (glass and frames), as well as the influence of window properties (U- and g-value) to the life-cycle cost and environmental impacts have not been presented.

Along with the thermal transmittance and solar factor for windows, orientation, and climate data are significant factors for the life-cycle cost and environmental impacts of a window. The energy performance of a window depends not only on the window properties but also on its orientation and the climatic conditions of the location [23], [24]. A considerable amount of literature has studied the effect of window orientation and climatic conditions on the operational performance of buildings (lighting, heating, and cooling load). Mangkuto et al. [25] investigated the influence of window area and orientation on the various daylight metrics and lighting energy demand in buildings. The results showed that the optimal window solutions in terms of daylight metrics and lighting energy demands were south-facing windows with about 30% window-to-wall ratio. Alghoul et al. [26] assessed the influence of window area and orientation on the heating and cooling energy consumption of an office in Libya. Several studies have looked at the influence of window orientation and climatic conditions on the operational energy and life cycle cost [27]–[30]. For example, Pikas et al. [27] considered possible window design solutions and orientations for the office buildings in the cold Estonian climate, taking both cost optimality and energy efficiency into account. Yasar et al. [30] used energy simulation software to investigate the effects of different glazed units and orientations on the energy needs and operating cost of high-rise residential buildings in moderate-humid climate regions of Turkey.

The operational stage is generally the main contributor to the total life-cycle impacts; however, if windows are more energy efficient the contribution of embodied impacts increases. This aspect has not been thoroughly analyzed and, as mentioned before, the literature has mainly focused on the operational performance of windows. Furthermore, there have been no comparative LC studies on windows that investigate the influence of high versus low U- and g-values, together with the effect of orientation and climate data on both economic and environmental life-cycle assessment. Thus, a comprehensive life cycle analysis should be performed to inform the wise selection of windows, considering their properties and components.

This article presents an integrated cost and environmental life-cycle analysis (LCA) of window solutions combining alternative glazing and framing options for office use. Pareto optimal window solutions were selected using a bi-objective optimization (costs vs. environmental impacts), considering various orientations and three different European climate regions. The influence of each window component (glass and frames), as well as window properties (U- and g-value) on the overall environmental and cost life-cycle assessment was investigated.

2. Materials and methods

An integrated environmental, energy and cost life-cycle analysis was implemented to calculate the cost and environmental impacts of alternative windows for a reference office room. Thermal dynamic simulation was employed to calculate operational energy using a calculation model previously validated with respect to EN 15265 (2007) [31]. This European Standard defines assumptions, boundary conditions and a procedure to validate dynamic calculation methods for the calculation of the annual energy needed to heat and cool spaces in a building or a part of it. Finally, a bi-objective optimization problem (costs vs. environmental impacts, for selected impact categories) was solved using Pareto optimal frontiers.

2.1. Life-cycle model and inventory

A life-cycle model and inventory was developed and implemented for 32 alternative window solutions (combining glazing and framing options), in a standard size (1.23 m × 1.48 m, based on ISO 10077-1 (2017) [32]). The functional unit selected was the total office area (19.80 m^2) over a period of 30 years, occupied by one person during working hours. The service life of a building is defined by its design, the construction methods and solutions used, user behavior, and maintenance strategy. Some of those factors are difficult to predict, so this research follows many other studies that have also assumed a 30-year lifespan for office buildings [15], [33], [34]. The life-cycle model included the construction phase (for the opaque envelope of the office with alternative windows) and operation phase (for heating and cooling).

2.1.1. Window solutions and office room

The reference room is described in ISO 13791 (2004) [35], 5.50 m long, 3.60 m wide and with a height of 2.80 m. All opaque components of the room were considered as adiabatic, excluding the front wall (3.60 m × 2.80 m). Thermo-physical properties of the opaque elements of the room (listed in Table 1), were taken from the standard.

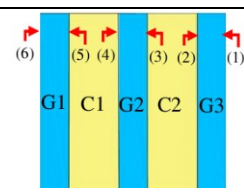
Table 1
Thermo-physical properties of the opaque elements of the reference office room [35]

Structure	Thickness, [m]	Thermal conductivity, λ	Density, ρ [kg/m^3]	Specific heat, C_p

		[W/ (m. K)]		[kJ/ (kg. K)]
Front wall				
Outer layer	0.115	0.99	1800	0.85
Insulation layer	0.060	0.04	30	0.85
Masonry	0.175	0.79	1600	0.85
Internal plastering	0.015	0.70	1400	0.85
Adiabatic walls				
Gypsum Plaster	0.012	0.21	900	0.85
Insulation layer	0.100	0.04	30	0.85
Gypsum Plaster	0.012	0.21	900	0.85
Ceiling / Floor				
Plastic covering	0.004	0.23	1500	1.50
Cement Floor	0.060	1.40	2000	0.85
Insulation layer	0.040	0.04	50	0.85
Concrete	0.180	2.10	2400	0.85

Table 2 shows the 41 cases studied: 32 alternative window solutions (4 frames × 8 glazing systems) + 8 glazing systems (without frame) + 1 baseline (wall without any window). The glazing solutions were selected based on low and high values for the thermal transmittance (U-value) and solar factor (g-value), within the commercially available range for different glazing types (single, double and triple) based on the Saint-Gobain Glass library [36], a leading manufacturer of flat glass for the European market. Cavities between the panes of glass were assumed to be filled with Argon gas. The alternative frame materials selected were aluminum (ALU), polyvinyl chloride (PVC), fiberglass (FGL) and wood (WOO). In addition, each glazing solution without a frame was considered (no framing windows, NOF), so as to compare the glazing solutions without the influence of the frame.

Table 2
Properties of the alternative window solutions selected



Window ID[1]	Glass layers (Glazing solution ID)	Glass type	Thickness guide in mm G_1-C_1-G_2-C_2-G_3 [2]	Coating type (coated surface number) [3]	Frame material (Framing ID)	U-value $W/(m^2K)$	g-value
NOF.S_SA[4]					no frame (NOF.S)	5.80	
ALU.S_SA					Aluminum (ALU.S)	5.84	
PVC.S_SA	Single (SA)	Annealed (A)	4A	-	PVC (PVC.S)	4.92	0.88
FGL.SD_SA					Fiberglass (FGL.SD)	4.95	
WOO.SDT_SA					Wood (WOO.SDT)	4.52	
NOF.S_SB					no frame (NOF.S)	5.60	
ALU.S_SB					Aluminum (ALU.S)	5.74	
PVC.S_SB	Single (SB)	Annealed (A)	8A	Solar control (2)	PVC (PVC.S)	4.82	0.39
FGL.SD_SB					Fiberglass (FGL.SD)	4.85	
WOO.SDT_SB					Wood (WOO.SDT)	4.43	
NOF.D_DA					no frame (NOF.D)	1.00	
ALU.D_DA	Double (DA)	Annealed (A)	6A-15-4A	Solar control (2)	Aluminum (ALU.D)	1.39	0.33
PVC.D_DA					PVC (PVC.D)	1.16	

FGL.SD_DA					Fiberglass (FGL.SD)	1.24	
WOO.SDT_DA					Wood (WOO.SDT)	1.24	
NOF.D_DB					no frame (NOF.D)	1.10	
ALU.D_DB					Aluminum (ALU.D)	1.46	
PVC.D_DB	Double (DB)	Annealed (A)	4A-16-4A	Low-e (3)	PVC (PVC.D)	1.23	0.65
FGL.SD_DB					Fiberglass (FGL.SD)	1.33	
WOO.SDT_DB					Wood (WOO.SDT)	1.31	
NOF.D_DC					no frame (NOF.D)	1.20	
ALU.D_DC					Aluminum (ALU.D)	1.54	
PVC.D_DC	Double (DC)	Tempered (T)	6T-12-6T	Solar control (2)	PVC (PVC.D)	1.30	0.35
FGL.SD_DC					Fiberglass (FGL.SD)	1.41	
WOO.SDT_DC					Wood (WOO.SDT)	1.39	
NOF.D_DD					no frame (NOF.D)	2.60	
ALU.D_DD					Aluminum (ALU.D)	2.56	
PVC.D_DD	Double (DD)	Laminated (L)	4A-16-6.4L	-	PVC (PVC.D)	2.31	0.78
FGL.DT_DD					Fiberglass (FGL.DT)	2.23	
WOO.SDT_DD					Wood (WOO.SDT)	2.40	
NOF.T_TA					no frame (NOF.T)	0.50	
ALU.T_TA					Aluminum (ALU.T)	0.87	
PVC.T_TA	Triple (TA)	Annealed (A)	4A-18-4A-18-4A	Low-e (2&5)	PVC (PVC.T)	0.74	0.62
FGL.DT_TA					Fiberglass (FGL.DT)	0.77	
WOO.SDT_TA					Wood (WOO.SDT)	0.87	
NOF.T_TB					no frame (NOF.T)	0.80	
ALU.T_TB					Aluminum (ALU.T)	1.10	
PVC.T_TB	Triple (TB)	Laminated (L)	6.8L-10-4A-10-4A	Low-e (2&5)	PVC (PVC.T)	0.96	0.58
FGL.DT_TB					Fiberglass (FGL.DT)	0.98	
WOO.SDT_TB					Wood (WOO.SDT)	1.09	

[1] Window system ID is expressed as frame ID_glazing ID.

[2] G_1: 1st glass pane thickness & type, C_1: 1st cavity thickness, G_2: 2nd glass pane thickness & type, C_2: 2nd cavity thickness, G_3: 3rd glass pane thickness & type.

[3] Glass surfaces are identified by number, starting with the exterior surface.

[4] NOF stands for no frame, ALU for aluminum, PVC for polyvinyl chloride, FGL for fiberglass, and WOO for wood framing.

The construction phase of the opaque envelope with the alternative windows includes raw material extraction and transport to the production site, production of the materials and their transport to the building site by lorry [37]. Table 3 presents the bill of materials for the front wall including the opaque envelope and alternative windows. Technical data of the opaque components was taken from Classen et al. [38]; Hischier and Gallen [39]; Kellenberger et al. [40]; and Werner et al. [41], framing from producers and suppliers, and glazing from the relevant environmental product declarations (EPDs) [36]. The front wall of the office room without a window was also considered (entirely opaque envelope) to better understand the economic and environmental influence of the windows used for the office room.

Table 3
Bill of materials for the front wall (10.08 m^2) including the opaque elements and alternative windows (1.82 m^2): i) opaque envelope; ii) unframed window; iii) aluminum-framed window; iv) PVC-framed window; v) fiberglass-framed window; vi) wood-framed window.

i) opaque envelope

Opaque envelope area, m^2	Mass of opaque components (kg)			
	Internal plastering	Insulating layer	Masonry	Outer layer
10.08 (no window)	211.68	18.14	2822.40	2086.56

8.26 (with window)	173.46	14.87	2312.80	1709.82

ii) unframed window

Window components	Mass of window components (kg)							
	NOF.S_SA[1]	NOF.S_SB	NOF.D_DA	NOF.D_DB	NOF.D_DC	NOF.D_DD	NOF.T_TA	NOF.T_TB
Glazing	18.20	36.40	46.66	37.66	55.58	46.89	58.11	66.28

iii) aluminum-framed window

Window components	Mass of window components (kg)							
	ALU.S_SA[2]	ALU.S_SB	ALU.D_DA	ALU.D_DB	ALU.D_DC	ALU.D_DD	ALU.T_TA	ALU.T_TB
Glazing	15.19	30.38	35.21	28.43	41.96	35.40	45.08	51.42
Framing	7.75	8.14	22.64	22.65	22.64	22.61	22.00	22.31

iv) PVC-framed window

Window components	Mass of window components (kg)							
	PVC.S_SA	PVC.S_SB	PVC.D_DA	PVC.D_DB	PVC.D_DC	PVC.D_DD	PVC.T_TA	PVC.T_TB
Glazing	14.61	29.22	34.51	27.85	41.12	34.67	41.51	47.35
Framing	36.02	36.23	25.99	26.01	25.99	25.95	32.07	29.88

v) fiberglass-framed window

Window components	Mass of window components (kg)							
	FGL.SD_SA	FGL.SD_SB	FGL.SD_DA	FGL.SD_DB	FGL.SD_DC	FGL.DT_DD	FGL.DT_TA	FGL.DT_TB
Glazing	15.10	30.20	38.71	31.25	46.11	33.37	41.35	47.18
Framing	13.24	13.17	12.89	12.92	12.89	18.75	18.02	18.37

vi) wood-framed window

Window components	Mass of window components (kg)							
	WOO.SDT_SA	WOO.SDT_SB	WOO.SDT_DA	WOO.SDT_DB	WOO.SDT_DC	WOO.SDT_DD	WOO.SDT_TA	WOO.SDT_TB
Glazing	13.46	26.92	34.51	27.85	41.12	34.58	42.98	49.02
Framing	17.40	17.26	16.68	16.72	16.68	16.63	15.88	16.34

[1] NOF stands for no frame, ALU for aluminum, FGL for fiberglass, and WOO for wood framing.
[2] Window IDs and the detailed information are presented in Table 2.

2.1.2. Operation phase

The operation phase was associated with the energy used for heating and cooling the office room with the alternative window solutions. For the occupancy pattern, the room was assumed to be occupied by one person from 8 am to 6 pm (in working days). The interior seasonal setpoints were considered as 20 °C for the heating season and 25 °C for the cooling season, with an air infiltration rate of 0.4 air changes per hour. A seasonal coefficient of performance (SCOP) of 3.40 for the heating season and a seasonal energy efficiency ratio (SEER) of 5.10 for the cooling season were adopted in accordance with energy efficiency class A [42]. Four cardinal directions for the window orientations were evaluated as well.

Three European locations were studied, considering different heating degree days (HDD) and cooling degree days (CDD), according to the Köppen−Geiger Climate Classification [43], [44]. The selected climate zones were categorized under the Köppen–Geiger classification system: a temperate climate with Mediterranean hot summer (Csa) represented by Portugal (Coimbra); a temperate oceanic climate (Cfb) represented by Germany (Berlin); and a semi-arid (steppe) desert climate (BSh) represented by Cyprus (Larnaca).

The energy needs (heating and cooling) of the room were calculated using EnergyPlus™ software [45]. The LC impacts per kWh of the annual electricity supply mix was calculated for Portugal based on Garcia et al. [46], and for Germany and Cyprus based on ecoinvent v.3.2. database [47].

2.2. Environmental life-cycle impact assessment methods

The following five impact categories were selected: cumulative energy demand (CED) for calculating non-renewable primary energy (NRPE) [48], global warming (GW, time horizon of 100 years), acidification (AC), eutrophication (EU) and ozone layer depletion (OD), from the CML 2001 method developed by the Institute of Environmental Sciences of the University of Leiden [49]. The selected impact categories follow the European standards: EN 15804 (2012) [50] and EN 15978 (2011) [51] and are commonly used in building LC studies [1], [52]. The LCA model and calculations have been performed using the SimaPro software.

2.3. Life-cycle costing method

Life-cycle costing was performed to calculate the global cost (€) in terms of net present value for the alternative window solutions, addressing the relevant costs, namely, construction costs (initial investment for the opaque envelope and alternative window solutions), and operational energy costs (covering both heating and cooling). The global cost calculation method followed by the Commission Delegated Regulation (EU) No 244 [53] includes the present value of the initial investment costs, running costs, and replacement costs if applicable.

A 3% discount rate has been assumed. Since the initial investment costs of the opaque envelope did not vary, the research focused on how the cost of the individual window components influenced the life-cycle cost results. The initial investment costs for the opaque envelope (65 €/m^2) and window solutions (as listed in Table 4) were provided by manufactures and suppliers. The electricity costs were derived from the European electricity price statistics for the three European climate zones: 0.229 €/kWh for Portugal, 0.300 €/kWh for Berlin, and 0.218 €/kWh for Cyprus [54].

Table 4
The initial investment costs for the alternative window solutions (€/1.82 m^2 window)

i) unframed window

Window components	Cost of window components (€/1.82 m^2 window)							
	NOF.S_SA[1]	NOF.S_SB	NOF.D_DA	NOF.D_DB	NOF.D_DC	NOF.D_DD	NOF.T_TA	NOF.T_TB
Glazing cost	33.59	134.35	167.93	67.17	257.50	78.37	123.15	156.74

ii) aluminum-framed window

Window components	Cost of window components (€/1.82 m^2 window)							
	ALU.S_SA[2]	ALU.S_SB	ALU.D_DA	ALU.D_DB	ALU.D_DC	ALU.D_DD	ALU.T_TA	ALU.T_TB
Glazing cost	28.03	112.14	126.79	50.72	194.41	59.17	95.55	121.61
Framing cost	571.95	571.95	473.55	473.55	473.55	473.55	861.00	861.00

iii) PVC-framed window

Window components	Cost of window components (€/1.82 m^2 window)							
	PVC.S_SA	PVC.S_SB	PVC.D_DA	PVC.D_DB	PVC.D_DC	PVC.D_DD	PVC.T_TA	PVC.T_TB
Glazing cost	26.95	107.79	124.19	49.68	190.43	57.96	87.94	111.93
Framing cost	248.58	248.58	261.01	261.01	261.01	261.01	285.87	285.87

iv) fiberglass-framed window

Window components	Cost of window components (€/1.82 m^2 window)							
	FGL.SD_SA	FGL.SD_SB	FGL.SD_DA	FGL.SD_DB	FGL.SD_DC	FGL.DT_DD	FGL.DT_TA	FGL.DT_TB
Glazing cost	27.85	111.41	139.26	55.70	213.53	55.77	87.63	111.53
Framing cost	496.21	496.21	496.21	496.21	496.21	432.10	432.10	432.10

v) wood-framed window

Window components	Cost of window components (€/1.82 m^2 window)							
	WOO.SDT_SA	WOO.SDT_SB	WOO.SDT_DA	WOO.SDT_DB	WOO.SDT_DC	WOO.SDT_DD	WOO.SDT_TA	WOO.SDT_TB
Glazing cost	24.84	99.35	124.19	49.68	190.43	57.96	91.07	115.91
Framing cost	625.00	625.00	625.00	625.00	625.00	625.00	625.00	625.00

[1] NOF stands for no frame, ALU for aluminum, FGL for fiberglass, and WOO for wood frame.
[2] Window IDs and the detailed information are presented in Table 2.

2.4. Pareto optimal frontiers

The concept of the Pareto optimal frontier (a set of non-dominated, non-inferior, or efficient solutions) introduces mathematical fundamentals for multi-objective problems. A solution is non-dominated when there is no other feasible solution that simultaneously ameliorates all the objective function values. In other words, ameliorating one of the objectives involves worsening at least one of the other objective function values [55].

The Pareto optimal frontier method was applied to a bi-objective problem (costs vs. environmental impacts, for each of the five selected impact categories). Pareto-optimal solutions are selected following the concept of dominance among vectors in the objective space [56]. In the dominance concept for minimization of two objective functions (the life-cycle cost and the life-cycle environmental impact of the alternative windows), a window solution x_1 dominates window solution x_2, if the objective function for x_1, which is $f(x_1)$, is better than the objective function for

x_2, which is $f(x_2)$, and x_1 is not worse than x_2 in at least one objective [57]. Therefore, x_1 is known as a non-dominated solution. In Pareto optimality, the dominance concept will be employed for all solutions to result in a set of Pareto optimal solutions that are non-dominated in the entire objective space [58].The mathematical expression of this is shown by the following two conditions:

$x_1 \succ x_2$ (window solution x_1 dominates window solution x_2) if

1) $f_j(x_1) \leq f_j(x_2)$, for j=1,2

2) $f_k(x_1) < f_k(x_2)$, for at least one $k = 1, 2$ ($j \neq k$)

Where $f_1(x_1)$ is the life-cycle cost of the window solution x_1, calculated as stated in the section 2.3; and $f_2(x_1)$ is the life-cycle environmental impact of the window solution x_1 (for the five selected impact categories), obtained as described in section 2.2.

Pareto optimal solutions consist of supported and unsupported efficient solutions. Fig. 1 illustrates the distinction between supported and unsupported non-dominated solutions in a bi-objective problem, with both functions to be minimized. The x-axis shows the life-cycle cost of the alternative windows which is $f_1(x_i)$ (where, i =1, 2, …, n, which is the number of window solutions), and the y-axis the life-cycle environmental impact which is $f_2(x_i)$ (in Fig. 1 shown for the global warming category). Supported non-dominated solutions are x_1, x_2 and x_4, and the unsupported non-dominated solution is x_3. The unsupported non-dominated solution (x_3) is dominated by some (infeasible) convex combinations of its two adjacent supported non-dominated solutions (x_2 and x_4). All convex combinations are defined by the intersection of the dominance cone stemming from x_3 with the segment connecting x_2 and x_4. Solution x_3 lies inside the convex hull defined by the supported solutions. The Pareto optimal frontier concept makes it possible to identify the set of non-dominated solutions for the window systems and show the trade-offs between the non-dominated solutions in terms of life-cycle cost and environmental impacts [55]. For this type of bi-objective problem with a limited number of window solutions, the Pareto optimal solutions can be graphically identified as illustrated in Fig. 1.

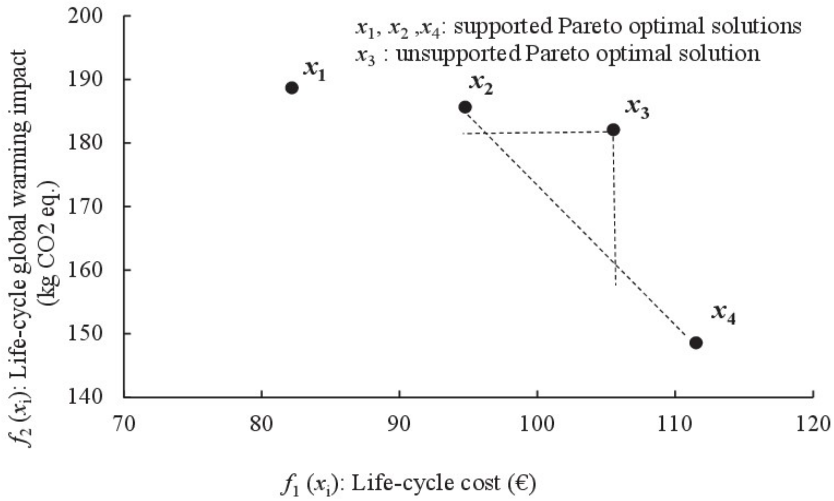


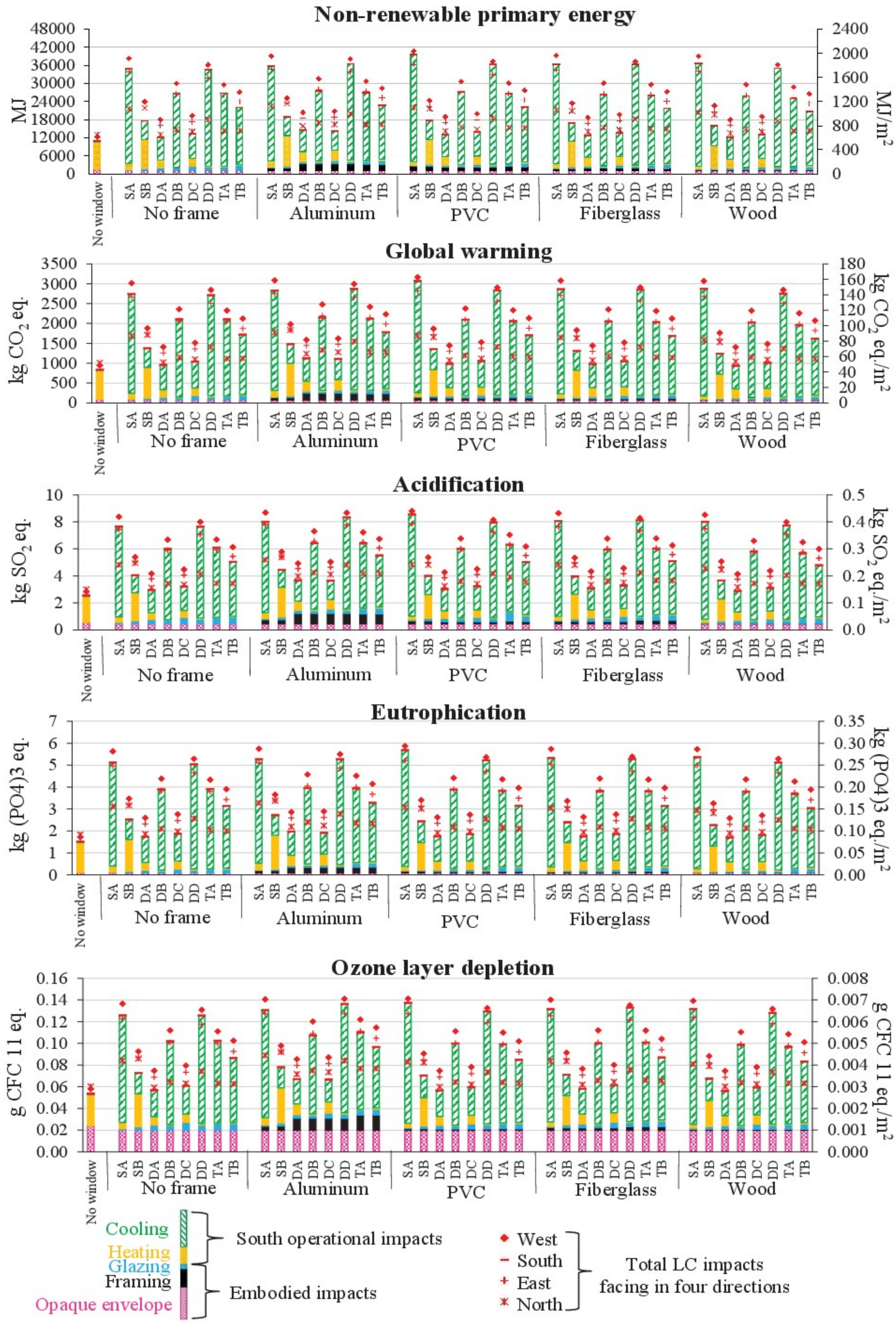
Fig. 1. Pareto optimal frontier consisting of supported and unsupported non-dominated solutions; an example for life cycle cost, f_1 (x_i), and global warming impact f_2 (x_i)

3. Results and discussion

This section presents the main results, namely, environmental life-cycle impact assessment (Section 3.1) and life-cycle costing (Section 3.2). Pareto optimal frontiers are presented (Section 3.3) based on the bi-objective optimization problem (costs vs. environmental impacts, for the five selected impact categories) to identify Pareto optimal window solutions.

3.1. Environmental life-cycle impact assessment

The life-cycle assessment of the components (opaque envelope, glazing and framing) and processes (construction and operation) were performed for the selected environmental impact categories, for the front wall with alternative windows and different orientations in the same climate region (Coimbra). Fig. 2 presents the LC environmental impacts of the 30-year use of the office room, comparing the alternative windows when fully exposed to the sun (no obstacle) from each of the four cardinal directions.



Non-renewable primary energy
MJ
MJ/m^2
Global warming
kg CO_2 eq.
kg CO_2 eq./m^2
Acidification
kg SO_2 eq.
kg SO_2 eq./m^2
Eutrophication
kg $(PO4)3$ eq.
kg $(PO4)3$ eq./m^2
Ozone layer depletion
g CFC 11 eq.
g CFC 11 eq./m^2
No window
SA SB DA DB DC DD TA TB
No frame
Aluminum
PVC
Fiberglass
Wood
Cooling
Heating
Glazing
Framing
Opaque envelope
South operational impacts
Embodied impacts
West
South
East
North
Total LC impacts facing in four directions

Fig. 2. LC environmental impacts of 30-year use of the office room in Coimbra, comparing different window solutions facing in four directions (a table with full results is presented as supplementary material)

The results are also presented by square meter of floor area for easier interpretation and comparison with other studies (as a secondary axis). The comparative assessment for the embodied impacts of the unframed windows shows that the double glazing solution using tempered glass (referenced as DC) and the triple glazing solutions (referenced as TA, TB) have the highest embodied impacts of all the solutions. The glazing solutions with low-e coating (DB, TA, TB, refer to Table 2) show significant EU embodied impacts, due to the electricity used in the production of the coating. The low-e film (copper oxide) contributes approximately 35% of the total embodied EU of the glazing system because copper provides the eutrophic conditions by depleting dissolved oxygen. The comparative assessment for the operational impacts of the unframed windows indicates that the glazing solutions with the lowest solar factor (SB, DA, DC, g-value<0.40) have lower operational (cooling) impacts, under direct exposure to the sun.

The comparative assessment for the embodied impacts of the framing options shows that wood is the option with the lowest embodied impacts for the five impact categories. The aluminum frame for the double- and triple-glazed solutions has the highest impacts in all categories. Compared with the embodied impacts of the unframed window solutions, adding the wood frame to each solution leads to a 14-24% reduction of the embodied impacts for the whole window, within all impact categories, while the aluminum frame leads to a 29-49% increase in the total embodied impacts.

The total embodied impact assessment involving the embodied impacts of the front wall with alternative windows shows that the aluminum frame for the double- and triple-glazed window solutions has the highest embodied impacts for all impact categories (51–62% of total embodied impacts), except for OD impacts. Conversely, the wood frame contributes the least (7–9%) to the total embodied impacts. Although the opaque envelope was a fixed variable in this study, its contribution to the total OD embodied emissions is acknowledged, owing to the insulating layer.

The total life-cycle impact assessment (embodied and operational) of the wall with framed window solutions facing south shows that the total embodied impacts of the wall with aluminum-framed windows contribute about 16-31% to the total LC impacts, while the figure for the PVC and fiberglass-framed windows is about 8-23%, and around 5-17% for wood-framed solutions. The glazing solutions with the highest solar factor (SA, DB & DD, g-value>0.40) have the most influence on the upper cooling energy needs of the room. The operational impacts from cooling accounts for 51–92% of total LC impacts, within all impact categories. The comparison between the operational impacts of the unframed glazing solutions and the framed ones indicates that the frame option leads to slight differences in the operational impacts.

The results of comparing the different orientations show that for the west orientation, all windows (except a single-glazed one with low g-value) have higher total LC impacts thanks to the higher cooling energy needs. Window solutions with the lowest solar factor (g-value<0.40) that face west offer considerably higher benefits than the other solutions, compared with the other orientations. For example, a low-solar factor window (ALU.D_DA; g-value 0.33) has 7% lower life-cycle NRPE impacts for the north orientation and 35% for the west orientation, when compared with a high-solar factor solution (ALU.D_DB; g-value 0.65). The operation phase is the greatest contributor in all scenarios, for all impact categories, accounting for 71-95%.

The office room was also analyzed in the other two climates (Berlin and Larnaca) in order to assess the influence of climate data on the LCA results. The life-cycle assessment of window components and processes was performed for the GW impact category, considering different shading strategies (with or without direct sun exposure) for the south orientation. Fig. 3 presents the GW impacts for the 30-year use of the office room in the three climate zones, comparing all the alternative windows. Three alternative European climate zones were considered: Coimbra (HDD 1304, CDD 424), Berlin (HDD 3155, CDD 170), and Larnaca (HDD 759, CDD 1260).

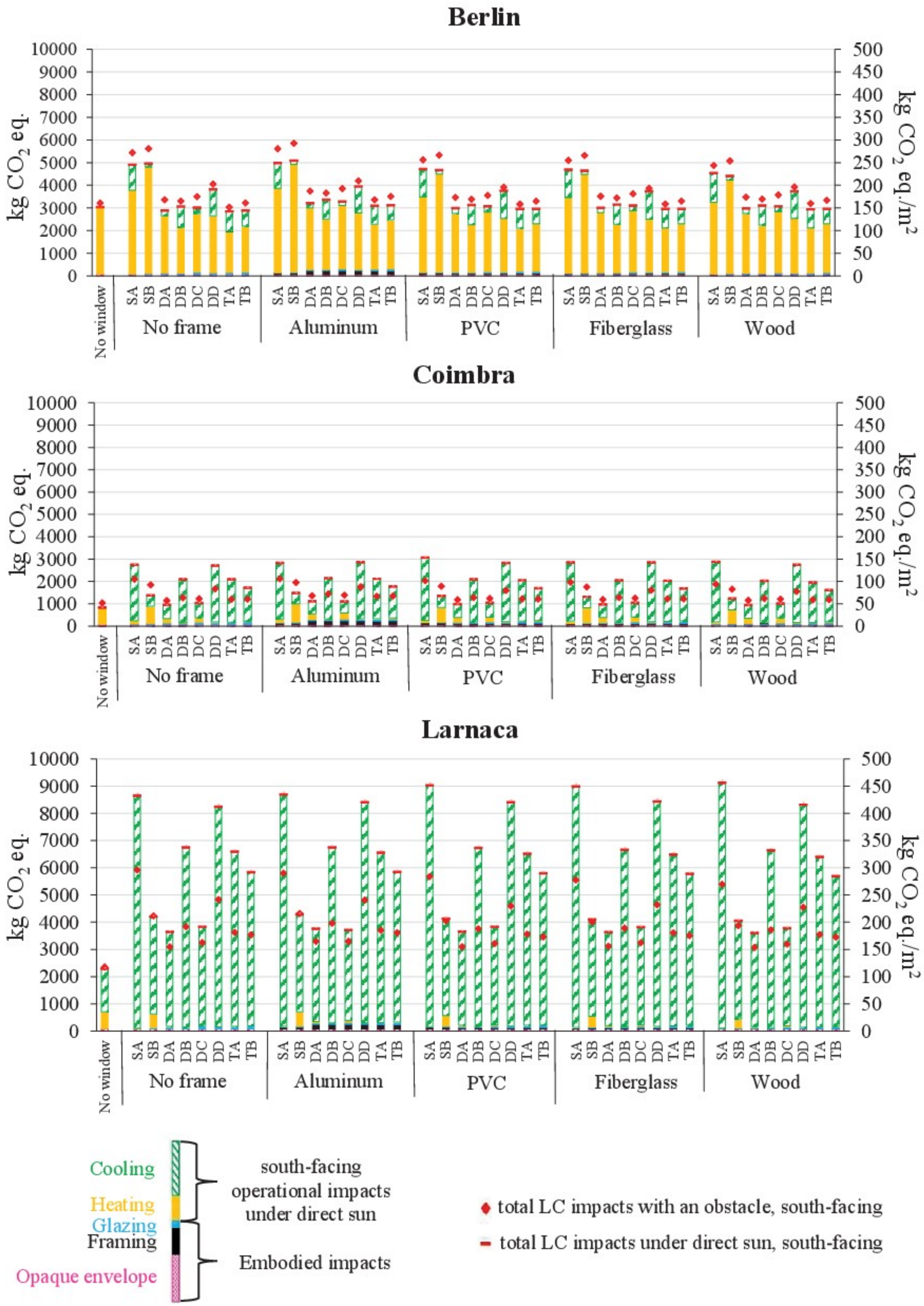


Fig. 3. Global warming impacts of 30-year use of the office room in three climate zones (Berlin, Coimbra and Larnaca), comparing different windows for south orientation, under direct sun or with an obstacle

The results indicate that the cooling energy needs are dominant in Coimbra and Larnaca. Thus, the window solutions with the lowest solar factor (SB, DA and DC, g-value<0.40) have lower operational impacts in warm climates than the high-solar factor windows (SA, DB, DD). When there is no obstacle, the operational impacts of the low solar factor windows are significantly lower than when there is an obstacle. For example in Larnaca, a low-solar factor window (ALU.D_DA; g-value 0.33) with direct sun exposure has a 43% lower GW impacts than a high-solar factor solution (ALU.D_DB; g-value 0.65), while if there is an obstacle it has a 16% lower GW impacts.

When comparing the life-cycle GW impacts of the 30-year use of the room with different framed windows and direct sun exposure, around 2941 kg CO_2 eq. was estimated as the lowest value in Berlin (for WOO.SDT_TA), 3604 kg CO_2 eq. in Larnaca (for WOO.SDT_DA), and 940 kg CO_2 eq. in Coimbra (by WOO.SDT_DA). If there is an obstacle, the GW impacts of the aforementioned windows were increased by 9% in Berlin and 22% in Coimbra, while it fell by 14% in Larnaca.

3.2. Life-cycle costing

This section first presents the life-cycle cost results for the 30-year use of the office room, and afterwards gives the trade-off results between life-cycle costing and annual operational energy needs. Fig. 4 shows the results for the front wall with the alternative windows and different orientations in Coimbra after assessment of the contribution of individual components and processes to the LC cost results. The initial investment relates to the costs of the opaque envelope, the glazing and framing solutions, and the operational costs of the heating and cooling energy needs.

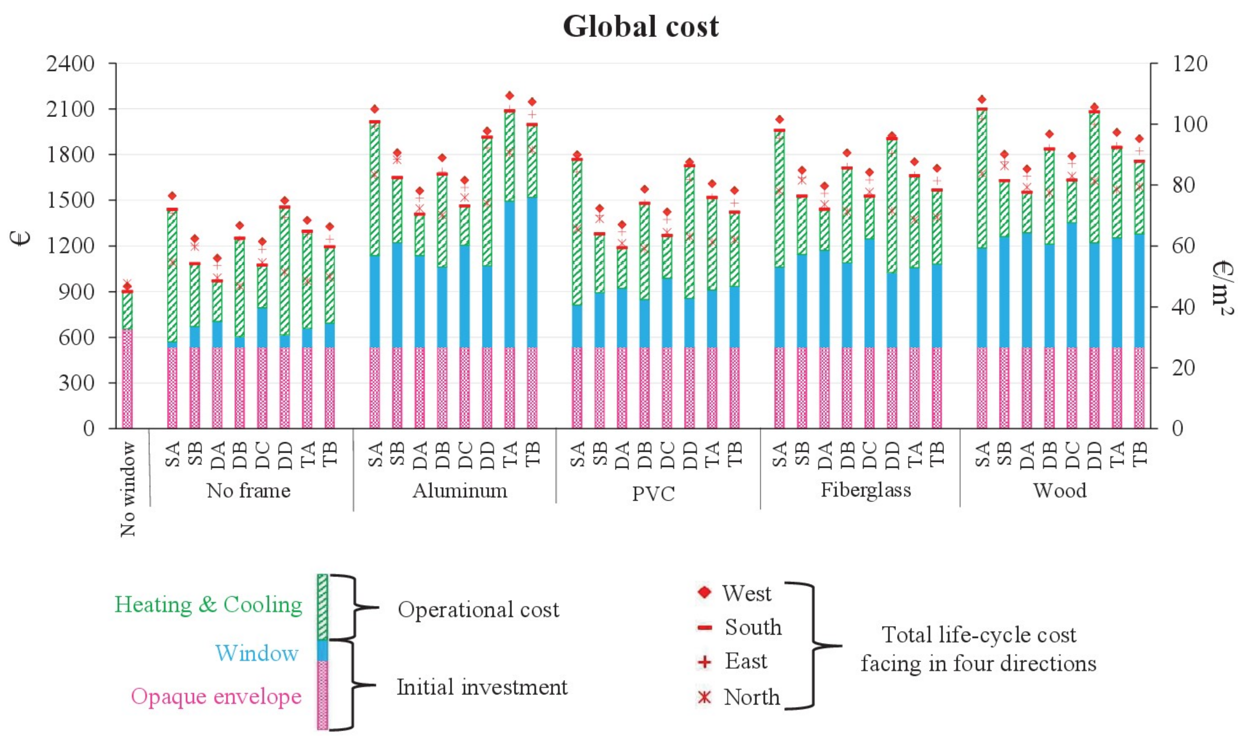


Fig. 4. Life-cycle cost of 30-year use of the office room in Coimbra, comparing different window systems facing in four directions

The results show that the cost-optimal glazing alternative is a double-glazed solution with a solar film since this has the lowest operational impacts. Comparing the framed solutions, we find that the aluminum and wood-framed windows require a higher initial investment cost than the other window alternatives. The PVC-framed windows lead to noticeably lower LC costs for all orientations due to the lower initial investment, e.g. 36 to 64% lower LC cost than the ALU-framed solutions. For instance, replacing the aluminum frame of the low solar factor window (DA) with the PVC frame leads to an LC cost reduction of 18% for the south orientation, or an LC cost reduction of 27% by replacing the wood frame of the low-solar factor window (DA) with the PVC frame.

The comparative assessment results for different orientations show that the west orientation for each alternative solution has a higher life-cycle cost, owing to the higher operational energy needs. Furthermore, the wall with the triple-glazed solutions and aluminum frame in the west orientation represents the highest LC cost (up to about €2186). The lowest life-cycle costs were found for the north orientation, except for the lower solar factor solutions (SB, DA and DC). While the lower solar factor solutions for the south orientation resulted in the lowest life-cycle costs compared with the other orientations.

Fig. 5 and Fig. 6 present the trade-off results for the global cost [€/m^2] and annual operational energy needs [kWh/ (m^2. year)] in the three climates, considering south orientation. These figures set out to assess the influence of the solar factor (see Fig. 5) and the thermal transmittance value (see Fig. 6) on the operational energy needs and LC cost. In Fig. 5, the size of the points is increased by the higher solar factor, while in Fig. 6 the size is a function of the thermal transmittance value. The cost-optimal window solutions appear in the lower bound of the LC cost, and the energy-efficient solutions in the lower bound of the operational energy needs. As can be seen, the cost-optimal window solutions are represented by the PVC-framed windows for the three climates, due to the lower initial investment of the PVC frames. For Larnaca and Coimbra, the energy-efficient windows are the solutions with the lowest solar factor (DA & DC, g-value< 0.40), as can be seen in Fig. 5 by the accumulation of the smallest points in the lower bound of operational energy needs. The window solutions with the lowest thermal transmittance values are found to be the energy-efficient ones for Berlin (U-value < 1.50 W/(m^2K)), as seen in Fig. 6 from the lower bound of operational energy needs filled with the small-sized points.

A comparison of the two groups of window solutions (cost-optimal and energy-efficient) shows that some solutions are present in both lower bounds. In Coimbra and Larnaca, two low-solar factor solutions (DA and DC, g-value<0.40) with the PVC frame (PVC.D_DA and PVC.D_DC) appear in both lower bounds. In Berlin, the low thermal transmittance solutions (U-value<1.50W/(m^2.K)) with the PVC frame (PVC.T_TA, PVC.T_TB, PVC.D_DA, PVC.D_DC, PVC.D_DB) have the lowest LC cost and operational energy needs.

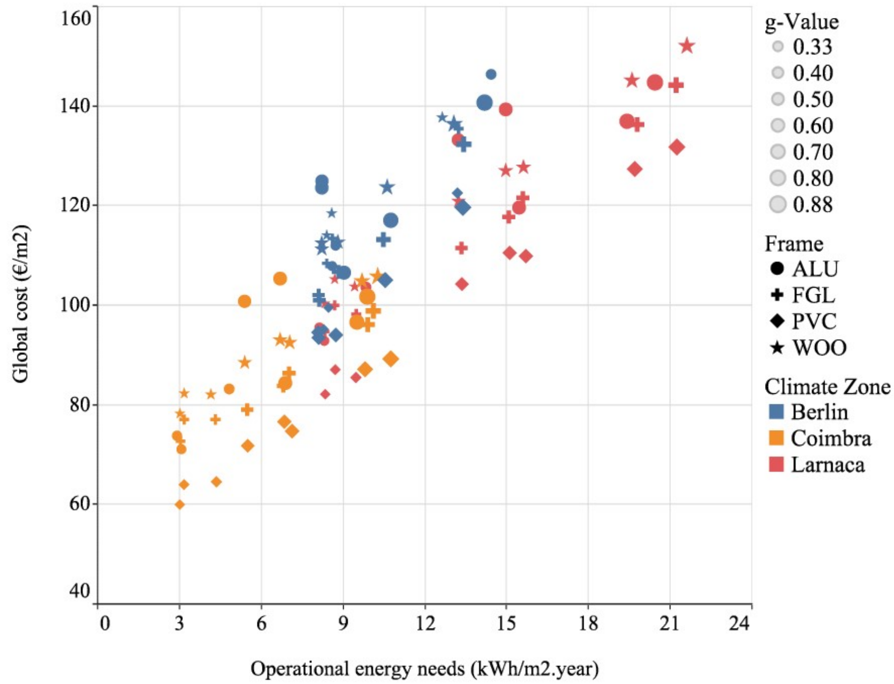


Fig. 5. Global cost (€/m^2) and annual operational energy (kWh/m^2.year) trade-offs for the office room with alternative windows facing south, comparing three climate regions (Coimbra, Berlin and Larnaca), and assessing the influence of the solar factor

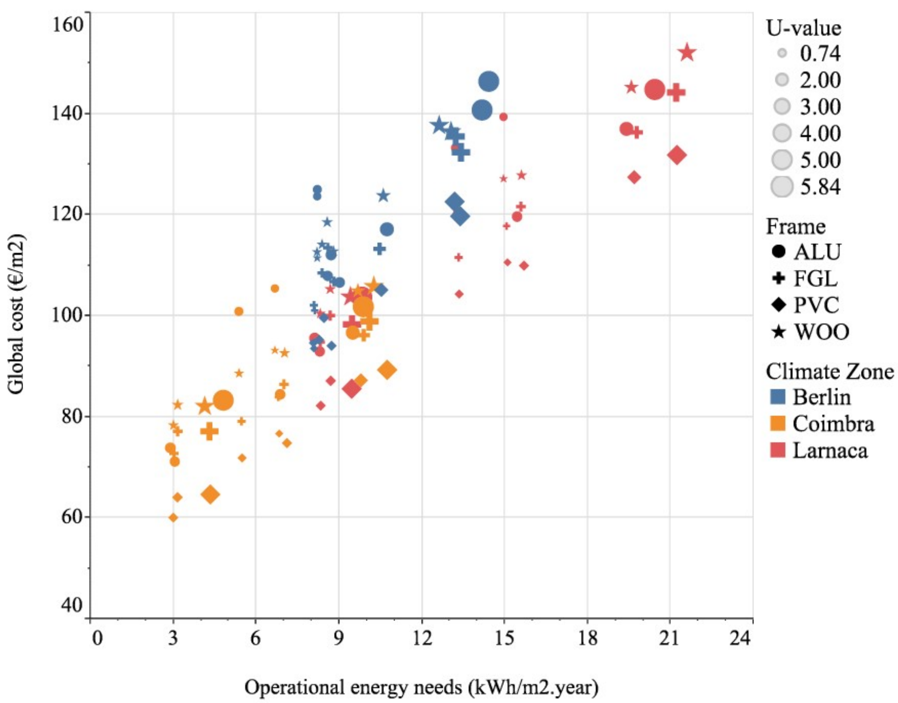


Fig. 6. Global cost (€/m^2) and annual operational energy (kWh/m^2.year) trade-offs for the office room with alternative windows facing south, comparing three climate regions (Coimbra, Berlin and Larnaca), and assessing the influence of the thermal transmittance value

3.3. *Pareto optimal window solutions*

A trade-off between the environmental and cost LCA has been made for the framed windows, for the five impact categories (NRPE, GW, AC, EU, OD). When considering the trade-offs between the LC cost and environmental impacts, the alternative windows in each climate region are dominated by a small number of the window solutions (Pareto optimal solutions).

Fig. 7 presents all the window solutions and the set of non-dominated window solutions positioned on the Pareto optimal frontiers. It further shows the trade-off between the cost and environmental LCA, for the five environmental impact categories. The Pareto optimal frontier consists of the supported and unsupported non-dominated solutions. In the set of non-dominated window solutions, since the following two solutions are common to all impact categories in Coimbra and Larnaca, they are the supported non-dominated solutions: a solar control double-glazing (DA) with a wood frame (WOO.SDT_DA) and with a PVC frame (PVC.D_DA); and the same is true for two window solutions in Berlin: a low-E coated triple-glazing (TA) with a wood frame (WOO.SDT_TA) and with a PVC frame (PVC.T_TA), except for the eutrophication and ozone layer depletion impact categories.

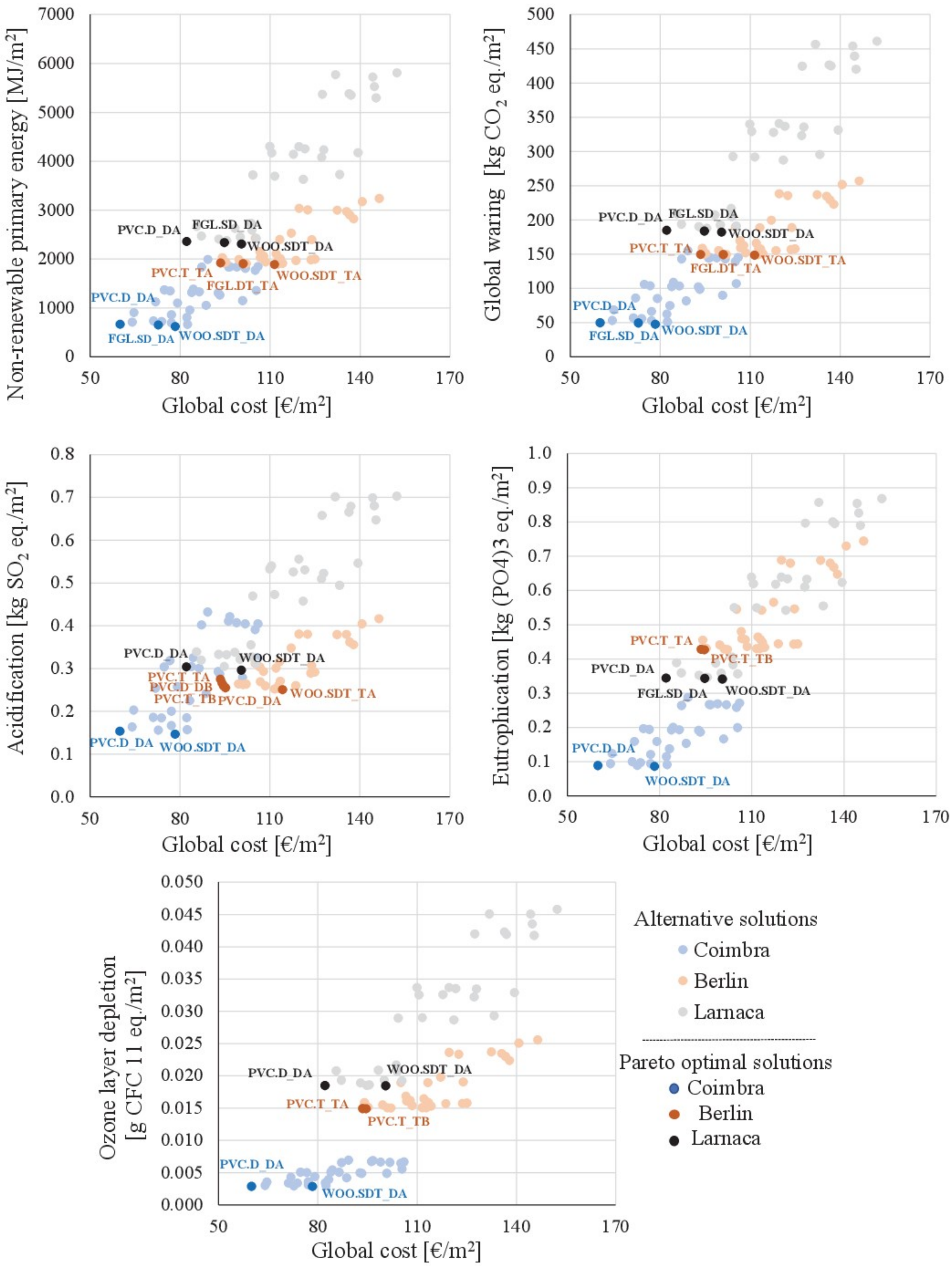


Fig. 7. The set of non-dominated solutions positioned on the Pareto optimal frontiers for the environmental and cost LCA of the alternative framed windows, in three climate zones: Coimbra, Berlin and Larnaca (south orientation)

A solar control double-glazing (DA) window with a fiberglass frame (FGL.SD_DA) is an unsupported non-dominated solution for the non-renewable primary energy and global warming, in Coimbra and Larnaca. In Berlin, the unsupported non-dominated solutions vary depending on the selected environmental impact category. Regarding non-renewable primary energy and global warming, the unsupported solution is the window with low-E coated triple-glazing (TA) and a fiberglass frame (FGL.DT_TA). For the ozone layer depletion, eutrophication and acidification, a laminated triple-glazing (TB) window with a PVC frame (PVC.T_TB) is the unsupported non-dominated solution. Regarding acidification, we can find the double-glazing (DA) window with a PVC frame (PVC.D_DA) and the laminated double-glazing (DB) window with a PVC frame (PVC.D_DB).

4. Conclusions

An integrated cost and environmental life-cycle assessment of 32 alternative window solutions for a reference office room has been presented. The 32 alternative windows combined four framing materials (aluminum, PVC, fiberglass, and wood) and eight glazing alternatives (low versus high values for thermal transmittance and solar factors). Four cardinal directions and three distinct European climates (Coimbra, Berlin and Larnaca) were assessed to explore how climate data and orientation influence the economic and environmental performance of the window solutions.

LC impacts were estimated for four environmental categories and non-renewable primary energy showing that glazing is the component with the greatest influence on the total environmental impacts (mainly operational because of heating and cooling energy needs). The impacts are highly dependent on the thermal transmittance values and solar factors; glazing solutions with the lowest solar factor showed lower operational (cooling) impacts in warm climates, and those with the lowest thermal transmittance values had lower operational (heating) impacts in cold climates. Framing options lead to slight differences in the overall impacts, mainly associated with the embodied impacts.

The life-cycle cost employed calculated the global costs of the alternative windows and showed that the PVC-framed windows lead to a noticeably lower LC costs for all orientations, due to the lower initial investment, e.g. 36 to 64% lower LC cost compared with the ALU-framed solutions. The comparative assessment results for different orientations show that the west orientation for each alternative solution involves a higher LC cost, owing to the higher operational energy needs. The wall with the triple-glazed window solution and aluminum frame facing west represents the highest LC cost (up to about €2186).

Looking at the results, the optimal window solutions that maximize LC benefits depend on the climate data and the orientation of the building. A low-solar factor solution is more beneficial in warm climate zones, and low thermal transmittance windows are better in cold climate zones. Even though the frame option does not offer significant operational savings, it can lead to lower embodied impacts. The results of this work have shown that the Pareto optimal window solutions in terms of economic criteria are the PVC-framed windows because of the low initial investment in the PVC frame. The Pareto optimal window solutions for all environmental impact categories in warm climates lead to the low solar factor windows with a PVC or wood frame. For cold climates, the Pareto optimal window solutions are associated with the window solutions with a low thermal transmittance value and with a PVC or wood frame.

The integrated LC approach with Pareto bi-objective optimization implemented in this article can effectively evaluate the environmental impacts and costs of window solutions and recognize optimum thermal transmittance values and solar factors. The glazing and frame solutions studied in this article cover a large range of the market in terms of thermal transmittance and solar factor. This article provides insights into and recommendations for the design of windows solutions by addressing different climatic conditions and window orientations. For future market solutions with values of thermal transmittance and solar factor differing from those presented in this article, new results and conclusions can be obtained by applying the proposed approach. In addition, the limitations of this study could be tackled by future research to address other parameters that affect the environmental and economic performance of windows, such as window area, lighting, occupancy level, and air ventilation rate.

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