Number of words: 7290

Embodied impacts of window systems: a comparative assessment of framing and glazing alternatives

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Highlights

- A comparative analysis of embodied impacts for alternative windows was performed.
- The contribution of framing and glazing components was analyzed.
- Tempered or laminated glass and coating considerably increase the embodied impacts.
- Aluminum frame accounts for 60 to 80% of the total window embodied impacts.
- Wood frame contributes less than 30% to the total window embodied impacts.

Abstract

The embodied impacts of window materials can be considered as hidden impacts. However, as buildings have become more energy efficient, the impacts of the windows are recognized as being increasingly significant and have not been thoroughly analyzed. Thus, comprehensive analysis should be performed to inform the wise selection of energy-efficient windows with lower embodied impacts. This article proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of a standard size window was implemented for 32 alternative systems, considering four framing materials (aluminum, fiberglass, polyvinyl chloride, wood) and eight glazing solutions (for single-, double, tripled-glazed). Environmental impacts were calculated for non-renewable primary energy, global warming, acidification, eutrophication, and ozone layer depletion. Pareto optimal frontiers were identified, showing the trade-offs between environmental impacts and thermal transmittance (U-value). The components of the two main parts of a window (frame and glass) have been characterized to identify those that contribute most to the total embodied impacts. The results show that tempered or laminated glass and the glass coating (low-E film) increase the embodied impacts of glazing solutions. Of the framing materials, wood has the lowest embodied impacts in all categories, while aluminum has the highest impacts for the double and triple-glazed solutions. The breakdown of the embodied impacts of aluminum-framed window systems shows that the frame has higher impacts than the glazing, as it accounts for 60-80% of total embodied impacts. In the windows with polyvinyl chloride (PVC) and fiberglass frames, the frame is responsible for most of the embodied impacts for single-glazed windows (58-86%) and almost the same proportion for double-glazed windows (46-54%), but lower for triple-glazed (22-40%). The contribution of a wood frame (<30%) is much less significant. Pareto optimal frontiers are identified for the window systems and the non-dominated solutions are discussed for the various environmental impact categories.

Keywords

Embodied impact; cradle-to-site; window system; glazing; framing; Pareto frontier

Nomenclature

		LCA	Life-cycle assessment
AC	Acidification	NRPE	Non-renewable primary energy
ALU	Aluminum frame	OD	Ozone layer depletion
ALU.D	Aluminum frame for double-glazing	PVB	Polyynyl butyral interlayer
ALU.S	Aluminum frame for single-glazing	PVC	Polyvinyl chloride frame
ALU.T	Aluminum frame for triple-glazing	PVC.D	PVC frame for double-glazing
A_n	Annealed glass type	PVC.S	PVC frame for single-glazing
CED	Cumulative energy demand	PVC.T	PVC frame for triple-glazing
D	Double-glazing	S	Single-glazing
DA	Double A glazing solution	SA	Single A glazing solution
DB	Double B glazing solution	SB	Single B glazing solution
DC	Double C glazing solution	t	ton
DD	Double D glazing solution	T	Triple-glazing
EE	Embodied energy	TA	Triple A glazing solution
EPD	Environmental product declaration	TB	Triple B glazing solution
EU	Eutrophication	T_e	Tempered glass type
FGL	Fiberglass frame	U	Thermal transmittance value
FGL.DT	Fiberglass frame for double- and triple-glazing	WOO	Wood frame
FGL.SD	Fiberglass frame for single- and double-glazing	WOO.SDT	Wood frame for single-, double- and triple-glazing
g	Solar factor	$\succ$	dominates
GW	Global warming	$\forall$	for all
km	kilometer	$\exists$	there exists
L_a	Laminated glass type	$\wedge$	and

1. Introduction

The embodied impacts of building materials can be considered as hidden impacts, away from the construction site and not visible to the user, but they are increasingly significant as buildings become more energy efficient [1], [2]. Embodied impacts of building materials are the sum of impacts (energy, environmental) required in the production and transportation, from raw material extraction to the building site, i.e. from 'cradle-to-site' [3]. Research and policy strategies have been focusing on reducing a building's operational energy [4], [5], while the embodied impacts of building materials have been overlooked. Basbagill et al. [6] highlighted the importance of addressing the embodied impacts of the building materials when improving energy efficiency of buildings. A reduction of operational impacts is normally associated with a rise in the contribution of embodied impacts related to building materials [7].

Windows are essential building components that provide a view of the outside, admit daylight, enable solar heat gain and air ventilation [8], [9], but they need to provide noise insulation, resistance to wind loads [10] and fire resistance [11]. However, nowadays the selection of windows is highly dependent on its thermal behavior and most studies assessing the impacts of windows have been focused on operation (heating and cooling needs), ignoring embodied impacts.

Decision about the type of window frame, number of pane of glasses (single, double or triple), the gas filling the cavity (e.g., air or argon), coatings (e.g. low emissivity or solar control) will influence embodied impacts. The studies that assessed the embodied impacts of windows have mainly addressing individual components of windows. The majority have focused on frames [12]–[14], while a few have analyzed glazing [15], [16]. For example, Sinha and Kutnar [12] assessed three framing materials (aluminum, PVC, wood) and showed that the carbon footprint for aluminum and PVC frames was respectively 4 and 2 times higher than for a wood frame. For the PVC framing system, polyvinyl chloride contributed 45% to the embodied carbon, with stainless steel contributing 25%. Regarding the aluminum framing, the main contributions to the embodied carbon were aluminum (70%) and fiberglass reinforced plastic (10%). Seo et al. [13] also analyzed the embodied impacts of an aluminum framing solution and found that aluminum is the main contributor to the embodied carbon (87%) of a window, due to the energy used in the smelting process. For glazing solutions, Syrrakou et al. [16] assessed the environmental impacts associated with the production of electrochromic (EC) glazing compared with various insulating glass units. The results showed that EC glazing could have lower environmental embodied impacts, plus lower cost, and better thermal and optical behavior.

From the literature review, we have concluded that are few studies addressing the embodied impacts of individual components of windows (glazing and framing and their constituents) and it is essential to break each individual window part down into its components to determine the key contributors to the total embodied impacts. In addition, there have been no comparative studies on the embodied impact assessment of windows which investigate the influence of thermal transmittance and solar factors, together with the effect of individual constituents of glazing and framing options on the total embodied impacts of a window solution. The enhancement of window designs has been mainly focused on mechanical, architectural, thermal, and acoustical aspects; however, environmental impacts are increasingly important and embodied impacts have not been thoroughly assessed.

This article proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of a standard size window (1.23 m × 1.48 m) was implemented for 32 window systems (based on four framing materials and eight glazing solutions), which are compared with a view to identifying environmentally preferable (Pareto optimal) solutions. A “cradle-to-site” analysis has been performed to calculate the embodied impacts, including raw material extraction and transport, manufacture of materials and components, as well as transport to the building site. Alternative framing materials with different thermal transmittances (aluminum, fiberglass, PVC, and wood), and glazing solutions (for single, double, tripled-glazed, from low to high values of thermal transmittance and solar factors) have been assessed to identify those that contribute most to the total embodied impacts. The combination of the selected glazing and framing alternatives gives a range of thermal transmittance of the whole window between 0.74 and 5.84 W/(m^{2}K). Finally, we present the Pareto optimal frontiers derived for the thermal transmittance versus environmental impacts, for five categories.

This article has four sections, including this introduction. Section 2 presents the materials and methods. Section 3 analyzes and discusses the main results. These relate to how the individual components contribute to the total embodied impacts for the different framing and glazing solutions, as well as the set of window solutions located in the Pareto optimal frontiers. Section 4 draws the conclusions.

2. Materials and methods

2.1. Window systems

2.1.1. Glazing solutions

Many glazing solutions are used in the windows of buildings including ones that use different types of glass, numbers of panes of glass and kinds of glass film. Regarding strength, glass can be classified as annealed, tempered (or toughened) and laminated. Annealed glass is the basic form of the product after the annealing process on the float glass, which allows the melted glass to cool gently to relieve any residual internal stresses in the glass. Tempered glass is four to five times stronger than annealed glass. This glass type is made by heating the annealed glass in a tempering furnace to approximately 650°C and then cooling it rapidly. Tempered glass is more resistant to breakage and there is less risk of injury or damage in the event of breaking because of shattering in small pieces. Laminated glass is made of two sheets of annealed or tempered glass together with Polyynyl Butyral (PVB) interlayer. Laminated glass provides more safety and security because, if it breaks, the broken pieces are held together by an interlayer which prevents any person or object from entering. There are different kinds of glass films according to the function that is required of them. Solar control films, for example, originally reduced solar heat gain and cooling energy needs in summer, but the same effect of reducing solar heat gain in winter increased heating energy needs. The other type is low-E film that not only plays the role of solar control film in summer but also prevents heat loss through windows in winter [17]. Fig. 1 presents the most common glazing compositions changing the number of panes and type of glass, adapted from the technical catalogue of a glass manufacturer [18].

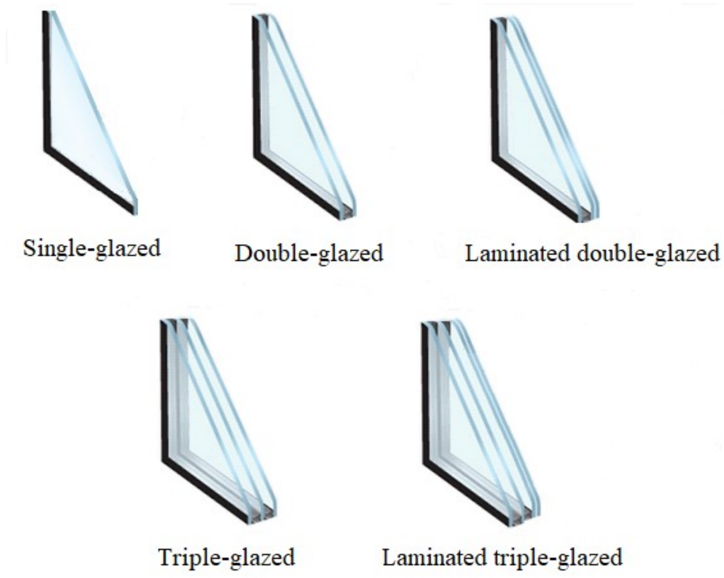


Fig. 1. Glazing compositions changing the number of panes and type of glass, adapted from [18]

In terms of the number of glass panes, there are three kinds of glazing systems, namely, single, double, and triple-glazed systems. A single-glazing solution is made of a single pane of glass (thickness ranges typically from 3 mm to 12 mm). Double- and triple-glazing solutions consist of two and three glass panes separated by an aluminum or plastic spacer and a gas filling (generally, air or argon) to improve the thermal efficiency. The spacer is bonded to the glass panes with a sealant and filled with a desiccant (typically a zeolite) to remove any moisture inside the cavity [17]. Fig. 2 presents a schematic design of a single-, double- and triple-glazing system, together with their components.

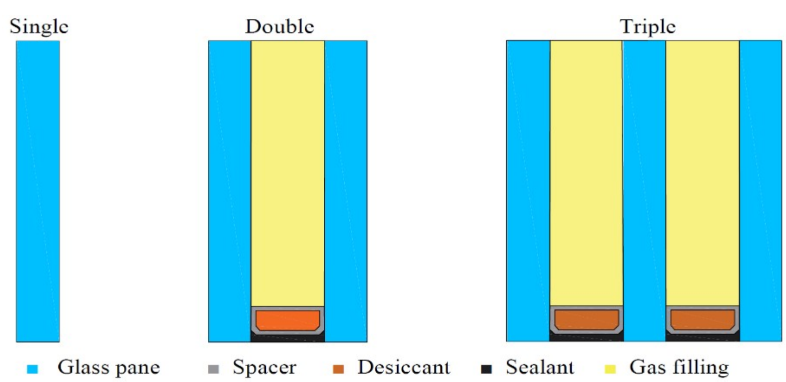


Fig. 2. Schematic design of single-, double- and triple-glazing solutions

Alternative glazing solutions were selected based on typical low and high values of thermal transmittance (U-value) and solar factor (g-value) within the commercially available range for the three glazing types.

Next, the type of glass (annealed, tempered and laminated) and films (solar control or low-E) for the solutions were chosen based on a library of a leading manufacturer of flat glass for the European market [19]. Glazing solutions were defined using Berkeley Lab Window 7.4 software [20], considering various glass types and films. Table 1 lists the alternative glazing solutions characterized by their optical and thermal properties. Cavities between panes of glass are filled with 100% Argon gas.

Table 1
Alternative glazing solutions characterized by thermal and optical properties

Glazing solution ID	Glass layers	Glass type	U-value (W/m^2K)	g-value	Total thickness in mm (G_1-C_1-G_2-C_2-G_3) [1]	Laminated form ($G_1G_2.N_L$) [2]	Coating type (face no. with coating) [3]	Coating material
Single A (SA)	Single	Annealed (A_n)	5.8	0.88	4.0 ($4A_n$)	-	-	-
Single B (SB)	Single	Annealed (A_n)	5.6	0.39	8.0 ($8A_n$)	-	Solar control (2)	Sodium fluorosilicate
Double A (DA)	Double	Annealed (A_n)	1.0	0.33	25.0 ($6A_n$-15-$4A_n$)	-	Solar control (2)	Sodium fluorosilicate
Double B (DB)	Double	Annealed (A_n)	1.1	0.65	24.0 ($4A_n$-16-$4A_n$)	-	Low-E (3)	Copper oxide
Double C (DC)	Double	Tempered (T_e)	1.2	0.35	25.0 ($6T_e$-12-$6T_e$)	-	Solar control (2)	Sodium fluorosilicate
Double D (DD)	Double	Laminated (L_a)	2.6	0.78	26.4 ($4A_n$-16-$6.4L_a$)	$3A_n3A_n.1$	-	-
Triple A (TA)	Triple	Annealed (A_n)	0.5	0.62	48.0 ($4A_n$-18-$4A_n$-18-$4A_n$)	-	Low-E (2&5)	Copper oxide
Triple B (TB)	Triple	Laminated (L_a)	0.8	0.58	34.8 ($6.8L_a$-10-$4A_n$-10-$4A_n$)	$3A_n3A_n.2$	Low-E (2&5)	Copper oxide

[1] 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.
[2] G_1: 1st glass pane thickness & type, G_2: 2nd glass pane thickness & type, N_L: number of laminated layers.
[3] Glass faces are identified by number, starting with the exterior surface.

2.1.2. Framing options

The most used frame materials are PVC, wood, and aluminum. Fig. 3 shows representative cross-section for each of these options.

Fig. 3. Cross-section images for PVC, wood, and aluminum frame options

PVC frames are reinforced with stainless steel inside, while in the case of aluminum, a low thermal conductivity element (thermal break) is fitted into the frame to reduce conductive energy losses. The thermal break is a low thermal conductivity material placed between internal and external metal parts of aluminum frame to prevent conductive thermal bridges. Fiberglass frame is also considered in this study as a solution that is growing in the market. Table 2 lists the components of the selected four frame materials (aluminum, PVC, fiberglass, and wood), and the relevant data sources.

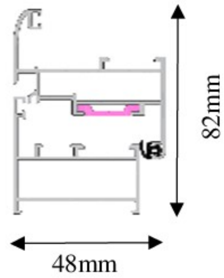
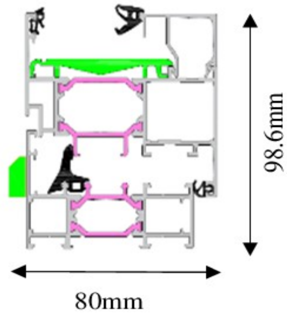
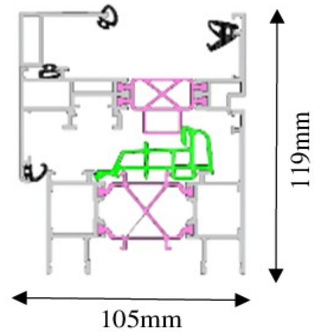
Table 2
Frame material components

Frame Components	Data source
Aluminum (ALU)	
-Aluminum	-Aluminum, produced at plant, mix of primary and secondary ALU with 32% share of secondary aluminum [21]
-Thermal break	-Fiberglass reinforced plastic, polyamide with a fiber content of 30% which is injected [22]
-Gasket	-Synthetic rubber, produced at plant [23]
-Weather stripping	-Silicone foam, copolymer, produced at plant [23]
Polyvinyl chloride (PVC)	
-PVC	-Polyvinyl chloride, produced at plant [22]
-Stainless steel	-Steel, low-alloy, produced at plant, containing less than 5% alloying elements in total [21]
-Gasket	-Synthetic rubber, produced at plant [23]
-Bonding inside	-Polystyrene foam, produced at plant [23]
Fiberglass (FGL)	
-Fiberglass	-Fiberglass, produced at plant [22]
-Adhesive tape	-Polyethylene, produced at plant [23]
-Gasket	-Synthetic rubber, produced at plant [23]
-PVC part	-Polyvinyl chloride, produced at plant [22]
Wood (WOO)	
-Softwood	-Sawn timber, softwood, produced at plant, carbon dioxide uptake is based on the carbon content of wood (49.4% of dry wood matter) [24]
-Gasket	-Synthetic rubber, produced at plant [23]

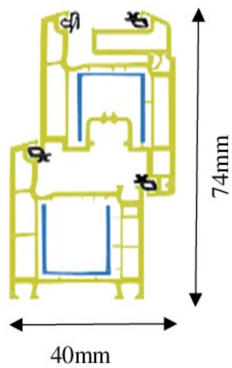
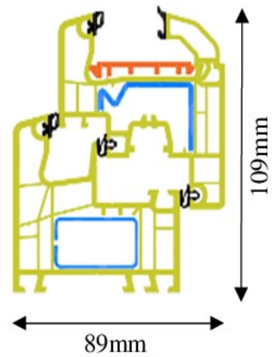
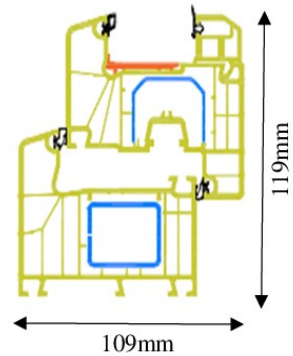
Each frame material is categorized into different frame types according to the characteristics of the applied glazing solution, such as number of panes and total thickness. Table 3 presents the selected framing options together with thermal transmittance values and the schematic designs. The schematic designs are representatives of solutions provided by different suppliers.

Table 3
Selected framing options

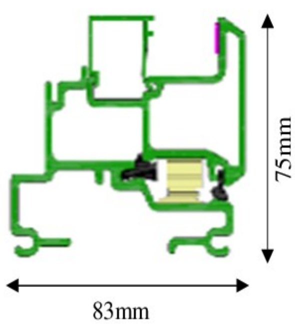
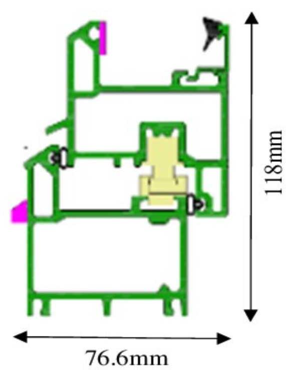
a) Aluminum Frame			
Solution ID	ALU.S [1]	ALU.D	ALU.T

Legend: Aluminum Thermal break Gasket Weather stripping			
Frame U-value (W/m^{2}K)	5.97	2.00	1.50

b) Polyvinyl chloride (PVC)

Solution ID	PVC.S	PVC.D	PVC.T
Legend: PVC Stainless steel Gasket Bonding inside			
Frame U-value (W/m^{2}K)	1.60	1.20	1.00

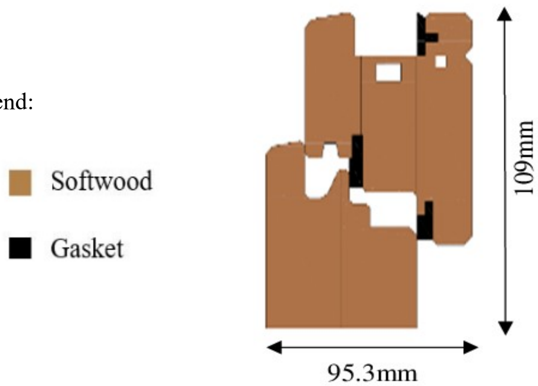
c) Fiberglass (FGL)

Solution ID	FGL.SD	FGL.DT
Legend: Fiberglass Adhesive tape Gasket PVC part		
Frame U-value (W/m^{2}K)	1.78	1.07

d) Wood (WOO)

Solution ID	WOO.SDT

Legend:



Frame U-value (W/m^{2}K) 1.52

[1] S stands for single, D for double and T for triple-glazing.
Note: The schematic design of framing solutions is a not-to-scale drawing.

Table 4 lists the bill of materials for standard size window systems measuring 1.23 m × 1.48 m [25] considering the full set of framing and glazing options. Thirty-two window systems are presented, consisting of four frame materials (listed in Table 3) and eight glazing solutions (listed in Table 2). Technical data were gathered from producers and suppliers for frames, and from environmental product declarations (EPDs) for glazing [19] to examine the properties and quantities of materials required for each window solution (foreground data). The U-values of the window solutions presented in Table 4 were calculated in accordance with ISO 10077-2 (2017) [26].

Table 4
Bill of materials for window systems with alternative glazing and framing materials: a) aluminum frame; b) PVC frame; c) fiberglass frame; d) wood frame.

a) aluminum frame

Window system ID[1]	U-value (W/m^{2}K)	Mass of framing and glazing components (kg/1.82m^2 of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Aluminum	Thermal break	Gasket	Weather stripping
ALU.S_SA	5.84	15.19	-	-	-	-	-	-	7.30	0.30	0.15	-
ALU.S_SB	5.74	30.38	-	-	-	-	-	-	7.69	0.30	0.15	-
ALU.D_DA[2]	1.39	34.35	-	0.26	0.34	0.23	0.03	-	14.96	4.03	1.47	2.18
ALU.D_DB	1.46	27.48	-	0.29	0.37	0.26	0.03	-	14.97	4.03	1.47	2.18
ALU.D_DC[2]	1.54	-	41.22	0.22	0.30	0.19	0.03	-	14.96	4.03	1.47	2.18
ALU.D_DD	2.56	34.35	-	0.29	0.37	0.26	0.03	0.10	14.93	4.03	1.47	2.18
ALU.T_TA	0.87	42.36	-	0.86	0.95	0.83	0.08	-	15.75	2.16	2.64	1.45
ALU.T_TB	1.10	49.42	-	0.48	0.56	0.45	0.04	0.47	16.06	2.16	2.64	1.45

b) PVC frame

Window system ID	U-value (W/m^{2}K)	Mass of framing and glazing components (kg/1.82m^2 of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	PVC	Stainless steel	Gasket	Bonding inside
PVC.S_SA	4.92	14.61	-	-	-	-	-	-	18.99	16.37	0.66	-
PVC.S_SB	4.82	29.22	-	-	-	-	-	-	18.86	16.37	0.66	0.34

PVC.D_DA[2]	1.16	33.65	-	0.26	0.34	0.23	0.03	-	13.12	11.00	0.81	1.06
PVC.D_DB	1.23	26.92	-	0.28	0.36	0.26	0.03	-	13.14	11.00	0.81	1.06
PVC.D_DC[2]	1.30	-	40.38	0.22	0.30	0.19	0.03	-	13.12	11.00	0.81	1.06
PVC.D_DD	2.31	33.65	-	0.28	0.36	0.26	0.03	0.09	13.08	11.00	0.81	1.06
PVC.T_TA	0.74	39.00	-	0.79	0.87	0.77	0.08	-	15.72	14.81	0.84	0.70
PVC.T_TB	0.96	45.50	-	0.44	0.52	0.42	0.04	0.43	15.17	13.36	0.65	0.70

c) fiberglass frame

Window system ID	U-value (W/m^2K)	Mass of framing and glazing components ($kg/1.82m^2$ of window area)										
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Fiberglass	Polyethylene adhesive tape	Gasket	PVC part
FGL.SD_SA	4.95	15.10	-	-	-	-	-	-	11.28	0.47	0.50	0.99
FGL.SD_SB	4.85	30.20	-	-	-	-	-	-	11.21	0.47	0.50	0.99
FGL.SD_DA[2]	1.24	37.75	-	0.29	0.38	0.26	0.03	-	10.93	0.47	0.50	0.99
FGL.SD_DB	1.33	30.20	-	0.32	0.41	0.29	0.03	-	10.96	0.47	0.50	0.99
FGL.SD_DC[2]	1.41	-	45.30	0.24	0.33	0.21	0.03	-	10.93	0.47	0.50	0.99
FGL.DT_DD	2.23	32.38	-	0.27	0.35	0.25	0.03	0.09	15.85	0.83	0.76	1.31
FGL.DT_TA	0.77	38.85	-	0.79	0.87	0.76	0.08	-	15.12	0.83	0.76	1.31
FGL.DT_TB	0.98	45.33	-	0.44	0.52	0.42	0.04	0.43	15.47	0.83	0.76	1.31

d) wood frame

Window system ID	U-value (W/m^2K)	Mass of framing and glazing components ($kg/1.82m^2$ of window area)								
		Annealed glass	Tempered glass	Sealant	Space bar	Desiccant	Argon	PVB interlayer	Softwood	Gasket
WOO.SDT_SA	4.52	13.46	-	-	-	-	-	-	16.16	1.24
WOO.SDT_SB	4.43	26.92	-	-	-	-	-	-	16.02	1.24
WOO.SDT_DA[2]	1.24	33.65	-	0.26	0.34	0.23	0.03	-	15.44	1.24
WOO.SDT_DB	1.31	26.92	-	0.28	0.36	0.26	0.03	-	15.48	1.24
WOO.SDT_DC[2]	1.39	-	40.38	0.22	0.30	0.19	0.03	-	15.44	1.24
WOO.SDT_DD	2.40	33.65	-	0.28	0.36	0.26	0.03	0.09	15.39	1.24
WOO.SDT_TA	0.87	40.38	-	0.82	0.90	0.80	0.08	-	14.64	1.24
WOO.SDT_TB	1.09	47.11	-	0.46	0.54	0.43	0.04	0.44	15.10	1.24

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

[2] The frame type selected for DA and DC according to each material option, are similar due to their equally total thicknesses.

Note: Glass films (solar control and low-E) are quantified by glass area because of their ultra-lightweight design.

2.2. Embodied impact assessment

To calculate the embodied impacts of a standard size window (1.23 m × 1.48 m), a ‘cradle-to-site’ model of the 32 alternative window systems was implemented to the following phases: raw material extraction, transport and manufacture of materials and components, as well as transport to the building site. The calculation had followed the Life Cycle Assessment methodology [27], [28], focusing on the ′cradle-to-site’ phases [3]. The main (foreground) data is the bill of materials (Table 4) presented in the previous section. Data for background processes (such as production of materials) were based on Althaus et al. [29]; Classen et al. [21]; Hischier and Gallen [23]; Kellenberger et al. [22]. Data for fuels for transportation was from Spielmann et al. [30]. Finishing materials were assumed to be locally transported, for an average 50 km distance (single trip in a 3.5-16t lorry) [30].

The 'cradle-to-site' model has been implemented in the SimaPro software [31]. The embodied energy have been calculated for non-renewable primary energy (NRPE) using the method cumulative energy demand (CED) [32]. Four environmental impact categories have been calculated, namely global warming 100-year time horizon (GW in kg CO_2 eq.), acidification (AC in kg SO_2 eq.), eutrophication (EU in kg PO_4 eq.), and ozone layer depletion (OD in kg CFC-11 eq.), using the CML 2001 method. These impact categories are recommended by European standards EN 15804 (2012) [33]; EN 15978 (2011) [34] and have been widely used in building LC studies [35], [36].

2.3. Interpretation of the results – 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 concurrently 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 [37].

The Pareto optimal frontier method was applied to bi-objective integer problems (U-value vs environmental impact, for each of the five impact categories). Pareto-optimal solutions are selected following the concept of dominance among vectors in the objective space [38]. According to dominance concept, solution x_1 dominates solution x_2 if the objective function for x_1 ($f(x_1)$) is better than the objective function for x_2 ($f(x_2)$) and x_1 is not worse than x_2 in at least one objective [39]. Therefore, x_1 is known as a non-dominated solution. In this study, the two objective functions to be minimized are the thermal transmittance and embodied impacts of window solutions. In Pareto optimality, the dominance concept will be employed for all solutions to result with a set of Pareto optimal solutions that are non-dominated in the entire objective space [40].The mathematical expression of this is shown in the following equation:

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

$\forall i: f_i (x_1) \leq f_i (x_2) \wedge \exists j: f_j (x_1) < f_j (x_2)$

where, j = 1, 2, ..., n, which is the number of objective functions.

Pareto optimal solutions consist of supported and unsupported efficient solutions. Fig. 4 illustrates the distinction between supported and unsupported nondominated solutions in a bi-objective problem, with both functions to be minimized. The x-axis shows the thermal transmittance (U-value) of window solutions $f_1 (x_i)$ and the y-axis the embodied impact $f_2 (x_i)$. Supported non-dominated solutions are x_1, x_2 and x_4, and 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 U-value and embodied impacts.

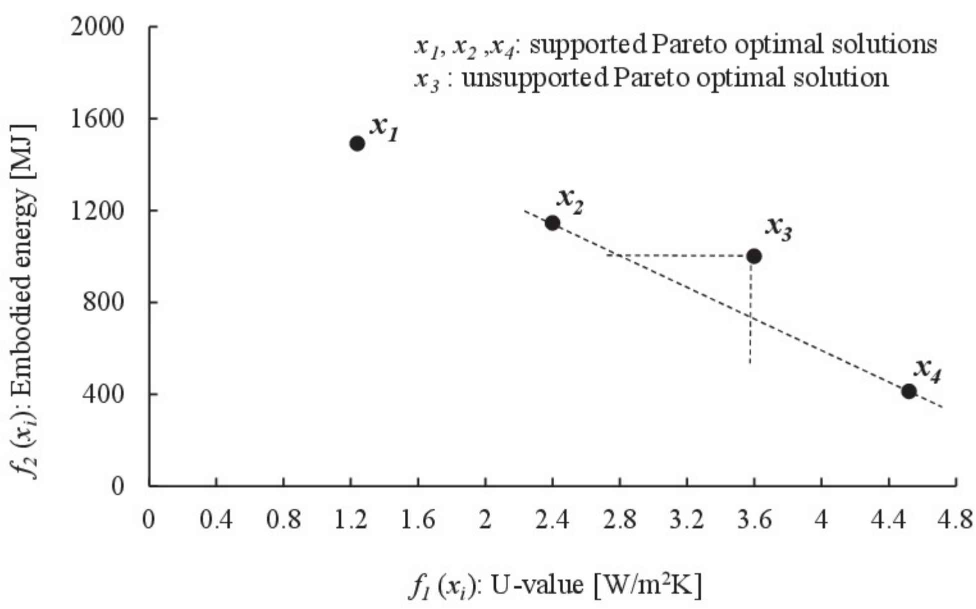


Fig. 4. Pareto optimal frontier consisting of supported and unsupported non-dominated solutions

3. Results and discussion

The embodied impacts for the window systems consisting of alternative framing and glazing solutions are analyzed and discussed in this section. Section 3.1 compares the embodied impacts of the alternative glazing solutions and framing options. The section concludes by describing the embodied impacts of the alternative window systems to show the contribution of glazing and framing. In Section 3.2, Pareto optimal frontiers are presented based on the multiple objectives (thermal transmittance vs. environmental impacts, for five categories) to identify optimal window solutions.

3.1. Embodied impact assessment – window systems with glazing and framing alternatives

3.1.1. Glazing alternatives

This subsection presents the contribution of individual components to the total embodied impacts of each glazing solution (from 'cradle-to-site'), along with a comparative analysis of the embodied impacts of the eight glazing solutions, aiming to encourage the use of products with fewer environmental burdens.

Fig. 5 shows the embodied impacts of the eight glazing solutions for the standard size and frameless window. Glass is the most significant glazing component as it accounts for more than 62% of the total embodied impacts of a glazing solution. Tempered glass is the largest contributor in Double C for all impact categories (about 95%), and is almost 1.5 times higher than the annealed glass because of the tempering process [41]. For the laminated glazing solutions (in Double D & Triple B), the PVB interlayer accounts for 15% and 20% of total GW and NRPE embodied impacts, respectively. For eutrophication, glass coating (low-E) has significant impacts because of the electricity used in its production. The low-E film (copper oxide) contributes approximately 35% of the total embodied EU of the glazing system as copper provides the eutrophic conditions by depleting dissolved oxygen. The contribution of Argon gas (<0.04%) and sealant (<2%) is not significant (all categories).

The impacts for the five categories assessed show similar pattern with increasing impacts associated with the increasing weight of glass in the solutions, with some exceptions, namely the laminated glazing (Double D and Triple B) and low-E coated glazing solutions (Double B, Triple A and Triple B). The magnitude of impacts is different for the laminated glazing solutions regarding non-renewable primary energy and global warming, and for the low-E coated solutions regarding eutrophication and ozone layer depletion.

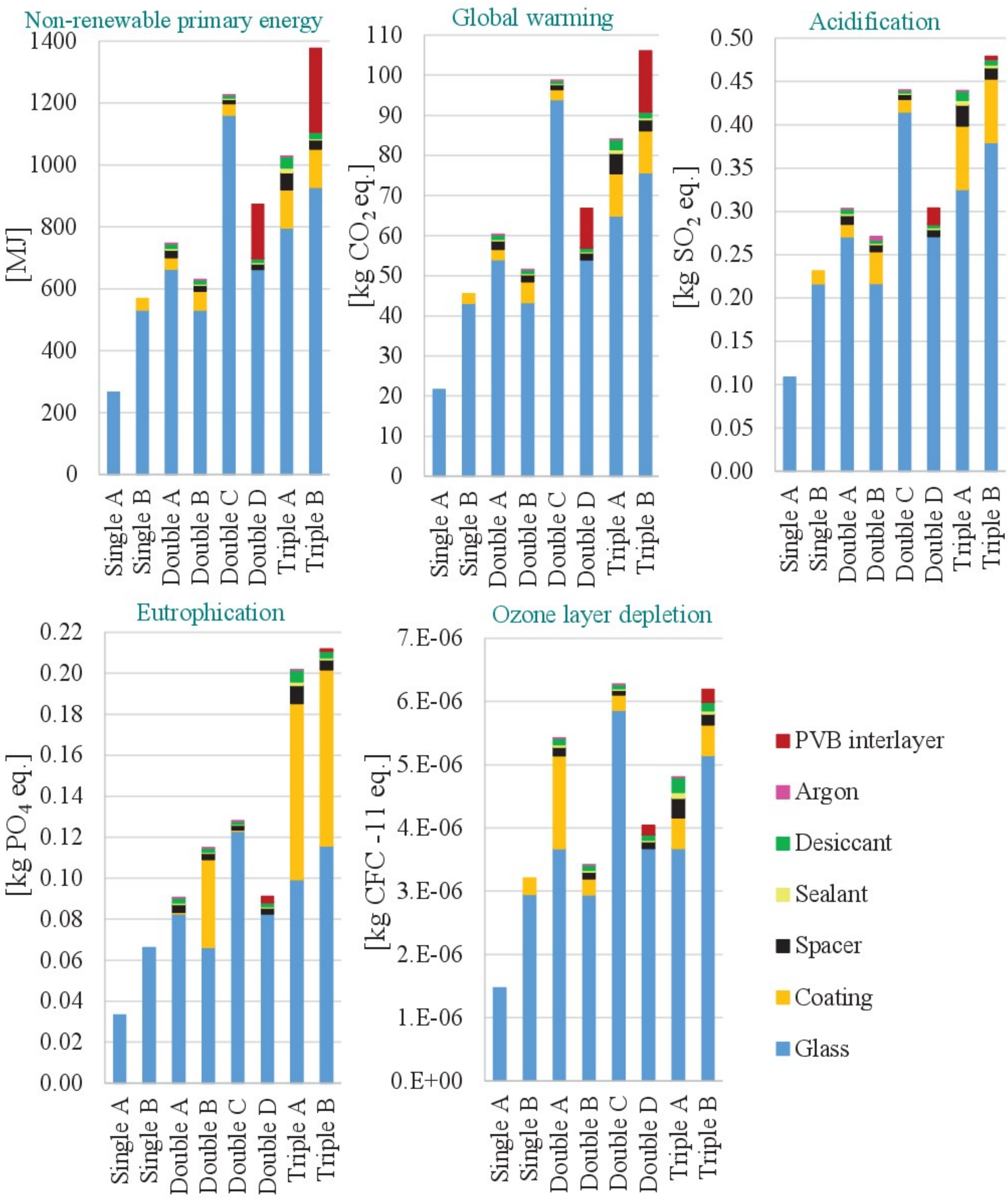


Fig. 5. Embodied impact assessment of eight alternative glazing solutions, by component, for 1.82 m^2 frameless window

3.1.2. Framing alternatives

The embodied impacts of the individual frame materials (ALU, PVC, FGL and WOO) were evaluated per component and then compared with the other framing alternatives for each environmental impact category. Fig. 6 presents the embodied impact assessment of the alternative framing for the standard size window. The results show that the wood frame is the option with the lowest embodied impacts among all categories. The aluminum frame for the double- and triple-glazed solutions (ALU.D & ALU.T) has the highest impacts in all categories. Regarding embodied energy, aluminum is the largest contributor in the ALU frame options (62-93%), followed by thermal break (10-23%), weather stripping (4-10%) and gasket (3-10%). PVC is the main contributor in the PVC frame solutions (60-66%), followed by stainless steel (24-29%), bonding inside (4-9%) and gasket (4-6%). Fiberglass in the FGL frame options has the highest share of embodied impacts (~74%), then nearly equal shares for the polyethylene adhesive tape, gaskets, and PVC part (6-10%). The WOO frame option is made of wood and gaskets, with approximately equal contributions to the total embodied impacts. Stainless steel is the component with the highest embodied eutrophication impacts for the PVC frame solutions, due to the galvanizing process (coating steel with zinc). For the ALU frame options, the thermal break contribution is nearly one-fourth of aluminum to terrestrial acidification and eutrophication and almost 20% for the other categories. These results provide a useful indication on the influence of each frame component on the embodied impacts of the different framing material options.

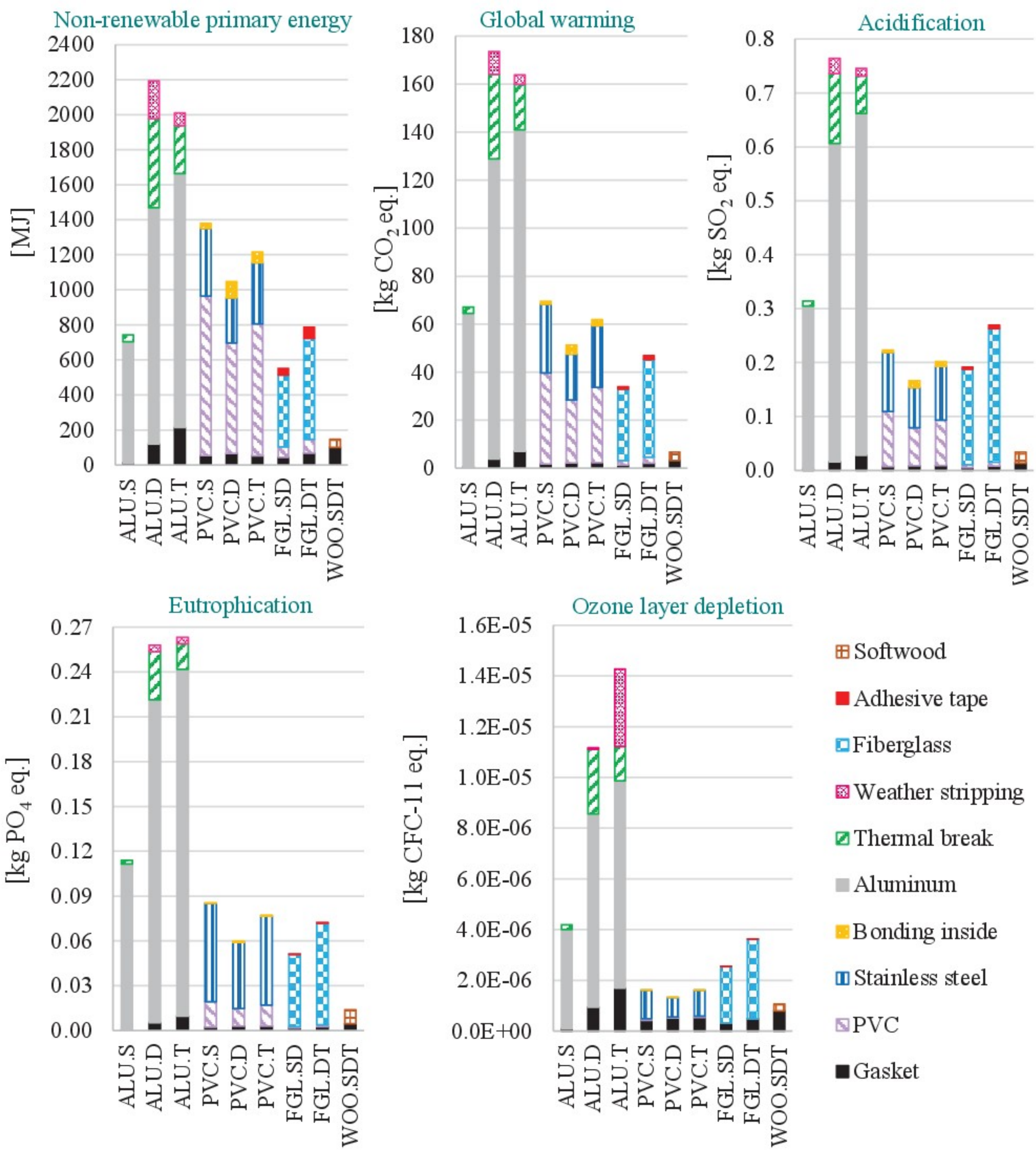


Fig. 6. Embodied impact assessment of four frame material options per component, for a standard size window

3.1.3. Alternative window systems

Fig. 7 presents the embodied impacts of the different window systems, for help understand the contribution of the individual glazing and framing solutions in each window system. The window systems and their thermal and optical properties are listed above, in Table 4. Fig. 7 shows the magnitude of embodied impacts of both the glazing and framing solutions.

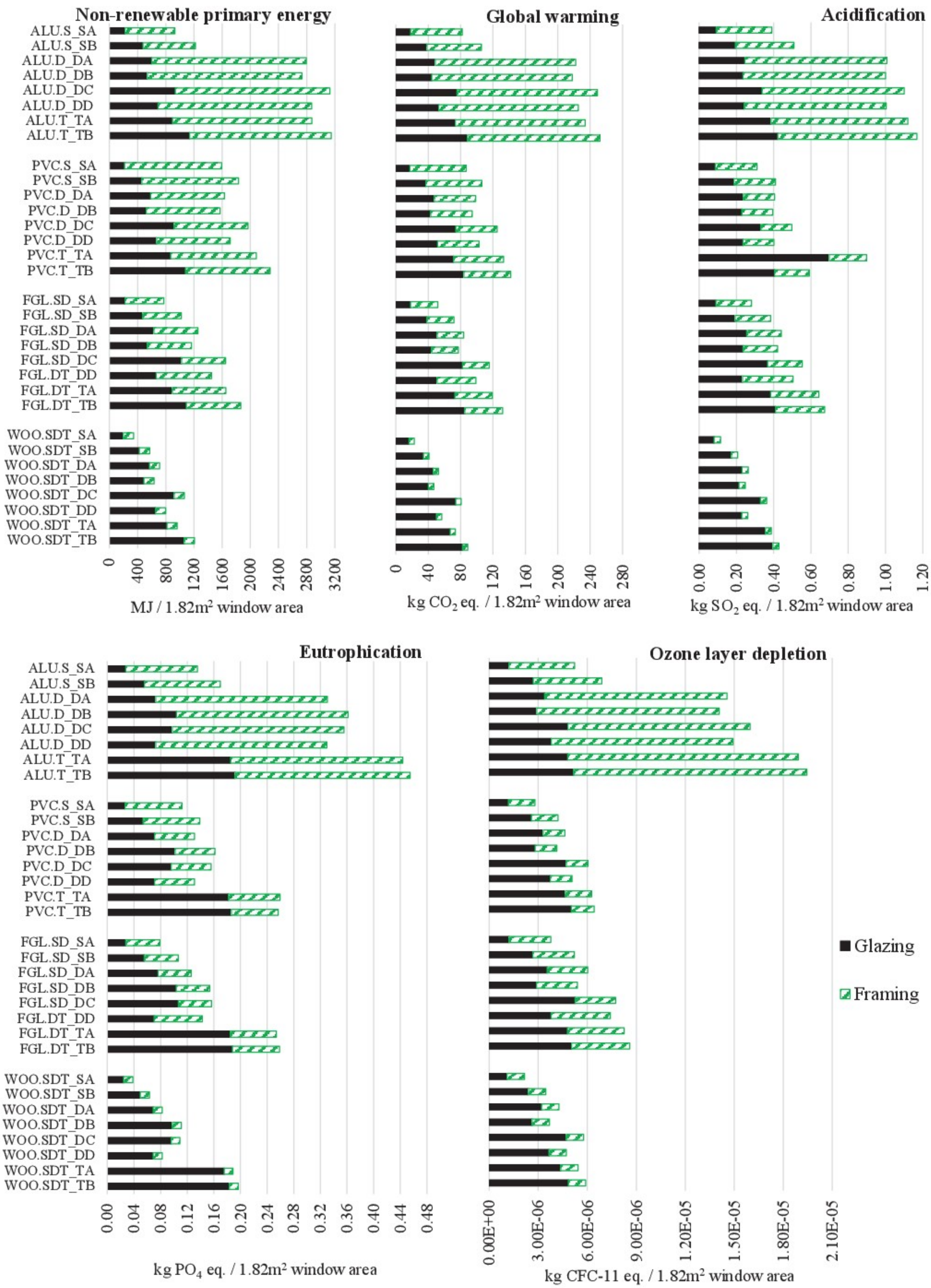
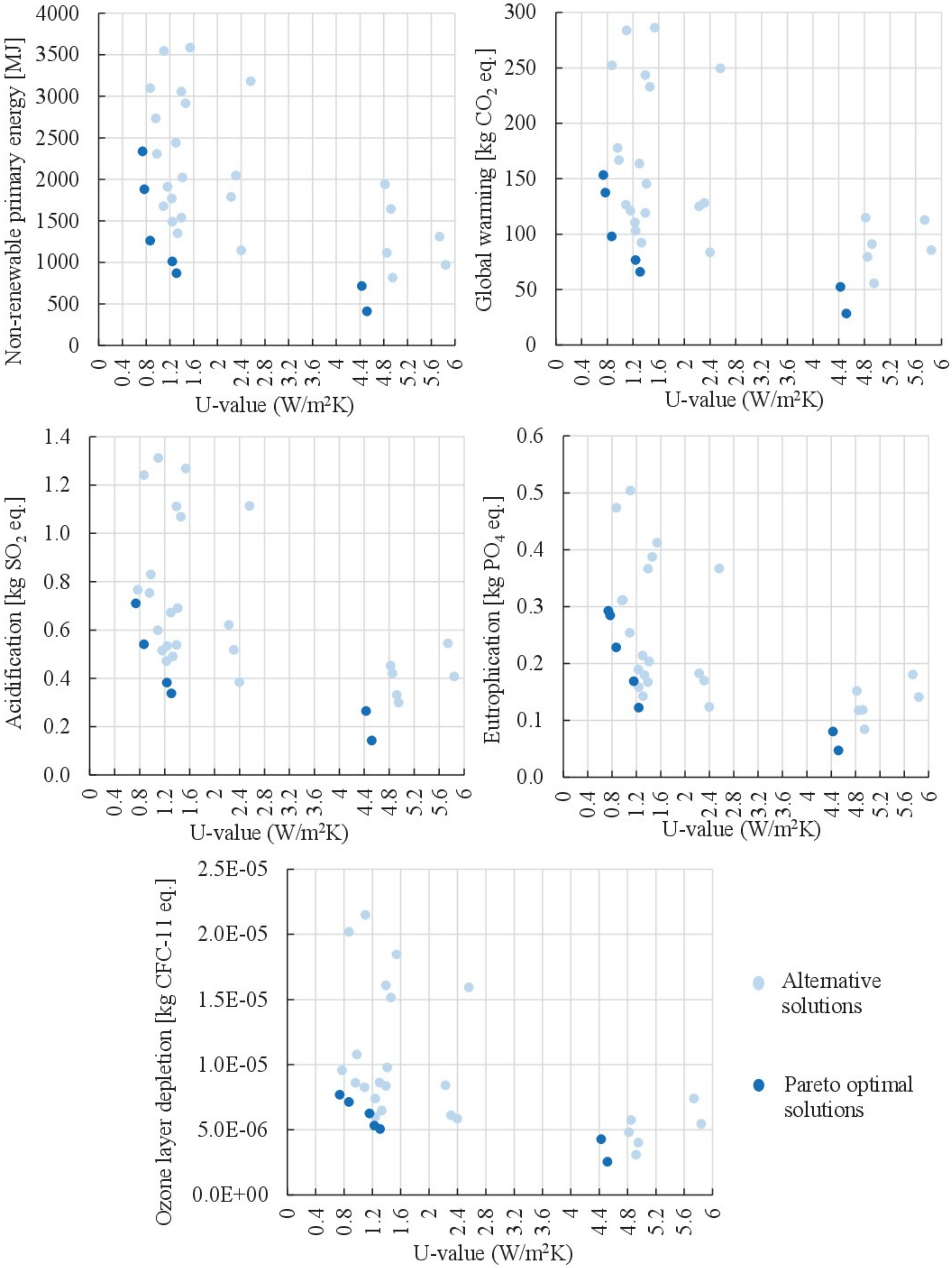


Fig. 7. Embodied impacts - breakdown of alternative window systems by glazing and framing solutions

For the aluminum frame window systems, the framing solution represents 60-80% of total embodied impacts. For the PVC and FGL frame window systems, the framing can have a low or high share of the total embodied impacts, depending on the selected glazing solution. The type of glazing influences the contribution; for the single-glazed options the highest embodied impact contribution comes from the framing (58-86%), a nearly similar contribution is found for double-glazed solutions and a smaller contribution with triple-glazed options (22-40%). The evaluation of these three examples shows that the glazing type has a significant influence on the embodied impacts share that needs to be considered. For wood frame solutions, the contribution of the framing (<30%) is much less significant (all categories).

3.2. Pareto optimal frontiers for the alternative window solutions

Fig. 8 shows the embodied impacts (discussed in the previous section) versus U-value for all window solutions, for each of the five impact categories. The x-axis shows the thermal transmittance values of window solutions and the y-axis the embodied impacts within the five environmental impact categories (NRPE, GW, AC, EU, and OD). Fig. 8 shows that most of the alternative window systems are dominated by a small number of window solutions namely Pareto optimal solutions marked in dark blue.



Non-renewable primary energy [MJ]
Global warming [kg CO_2 eq.]
Acidification [kg SO_2 eq.]
Eutrophication [kg PO_4 eq.]
Ozone layer depletion [kg CFC-11 eq.]
U-value (W/m²K)
Alternative solutions
Pareto optimal solutions

Fig. 8. Thermal transmittance and embodied impacts trade-offs for the alternative window solutions, with Pareto optimal solutions highlighted in dark blue

Fig. 9 identifies the set of non-dominated window solutions positioned on the Pareto optimal frontiers and shows the trade-off between the U-value and embodied impacts. In the set of non-dominated window solutions of the two-dimensional objective space for the five environmental categories, the following four window solutions are common to all categories: a low-E coated triple-glazing (Triple A, non-tempered and laminated) with wood frame (WOO.SDT_TA) or with PVC frame (PVC.T_TA); and two types of single-glazed solution with wood frame (WOO.SDT_SA and WOO.SDT_SB).

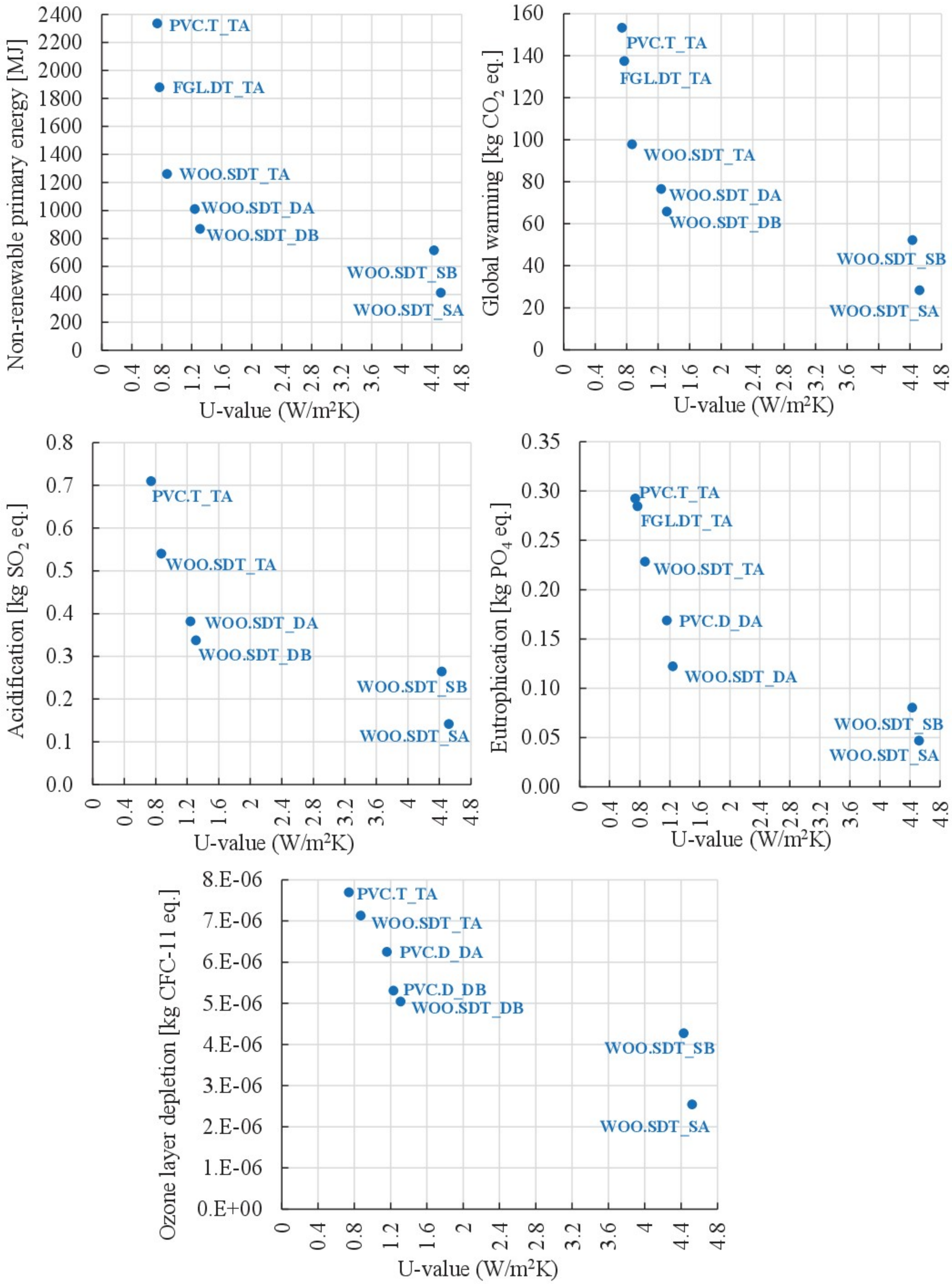


Fig. 9. Pareto optimal windows (thermal transmittance vs. embodied impacts)

The Pareto optimal frontier consists of supported and unsupported non-dominated solutions. The supported and unsupported non-dominated solutions for non-renewable primary energy and for global warming are the same. The set of supported non-dominated solutions is composed of a low-E coated triple-glazing (Triple A) with wood, PVC or fiberglass frame, and a low-E coated double-glazing (Double B) and a single glazing (Single A) with wood frames. The set of unsupported non-dominated solutions consists of a double-glazed solution with solar control film (Double A) and a single-glazed solution with solar control film (Single B) with wood frames. For eutrophication, the low-E coated double-glazing (Double B) is not positioned on the Pareto optimal frontier; instead a double-glazed solution with solar control film (Double A) with wood frame (as a supported non-dominated solution) and with PVC frame (as an unsupported non-dominated solution) appear on the Pareto optimal frontier. Regarding acidification and ozone layer depletion, the low-E coated triple-glazing (Triple A) with fiberglass frame is not located on the Pareto optimal frontier. The set of unsupported non-dominated solutions for ozone layer depletion comprises PVC- framed windows with two types of double-glazed solutions, Double A and Double B, and a wood-framed window with a single-glazing (Single B).

4. Conclusions

This article proposes an approach based on embodied impact assessment and Pareto optimal frontier to support environmentally friendly design of windows. A comprehensive assessment of the embodied environmental impacts of 32 window systems (four alternative framing and eight glazing solutions) was implemented. The most common framing materials (aluminum, fiberglass, PVC and wood) with other components (spacer, thermal break, weather stripping etc.), and single-, double, and tripled-glazed solutions (with coatings and gas-filled cavities) have been thoroughly assessed to ascertain the contribution of each component to the overall embodied impacts of the window system.

The embodied impacts calculated for the window systems show that for aluminum windows the contribution of the frame (>60% in all categories) is more significant than the glazing, while for wood-framed windows, the contribution of the framing is much less significant (<30% in all categories). For the PVC and fiberglass windows, the contribution of the framing varies depending on the glazing solution.

The assessment of the glazing alternatives shows that the embodied impacts are highly influenced by the type of glass. Tempered glass leads to higher embodied impacts for the five categories due to the tempering process. For laminated glass, a polyynyl butyral (PVB) interlayer, 0.38 mm thick, accounts for about 20% of total global warming (GW) and non-renewable primary energy (NRPE) embodied impacts. It should also be noted that the glass coating is one of the components with highest eutrophication (EU) impact due to the electricity consumed in the production process. A low-E film (copper oxide) contributes to approximately 35% of the total embodied eutrophication of the glazing system.

Regarding the framing materials, wood has the lowest embodied impacts, while aluminum frame has the highest. In the aluminum frame, the thermal break is responsible for up to 23% of the embodied impacts. Results for PVC frames show that the stainless steel used to ensure good mechanical resistance reaches a share of up to 29% of the embodied impacts.

Finally, Pareto optimal frontiers have been calculated so as to identify the set of non-dominated window solutions, showing the trade-off between thermal transmittance and embodied impacts (five categories). The results show that four window solutions are on the Pareto frontier for all categories: a low-E coated triple-glazing (Triple A, non-tempered and laminated) with a wood or PVC frame and two single-glazed solutions with wood frame.

The approach proposed in this article can help decision makers to choose windows according to the preferred objectives. This approach can be extended and applied to other window solutions, and to different desired objectives. The development of windows is commonly and mainly based on architectural, mechanical, thermal, and acoustical requirements. As environmental impacts and sustainability is of paramount importance, this article proposes an embodied impacts approach that can be applied during windows design to support the identification of components more environmentally friendly. To further improve the proposed framework, the full life-cycle should be addressed to calculate overall environmental impacts and costs.

Acknowledgments

We thank Professor Carlos Henggeler Antunes, University of Coimbra, for helpful discussions about the Pareto optimal frontier concept. The first author acknowledges financial support from the Portuguese Science and Technology Foundation through grant PD/BD/113537/2015. This work has also been supported by FCT project StreamLAB (MIT-EXPL/SUS/0013/2017), and by projects SET-LCA (CENTRO-01-0145-FEDER-030570) and T4ENERTEC (POCI-01-0145-FEDER-029820), co-funded by FEDER and FCT, and by the project EvoSlide (POCI-01-0247-FEDER-033658) and CorkAl (POCI-01-0247-FEDER-033814) funded by Portugal 2020 through COMPETE2020. The research presented in this article was carried out within the framework of the Energy for Sustainability Initiative of the University of Coimbra and the MIT Portugal Program.

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Nomenclature

AC	Acidification
ALU	Aluminum frame
ALU.D	Aluminum frame for double-glazing
ALU.S	Aluminum frame for single-glazing
ALU.T	Aluminum frame for triple-glazing
A_n	Annealed glass type
CED	Cumulative energy demand
D	Double-glazing
DA	Double A glazing solution
DB	Double B glazing solution
DC	Double C glazing solution
DD	Double D glazing solution
EE	Embodied energy
EPD	Environmental product declaration
EU	Eutrophication
FGL	Fiberglass frame
FGL.DT	Fiberglass frame for double- and triple-glazing
FGL.SD	Fiberglass frame for single- and double-glazing
g	Solar factor
GW	Global warming
km	kilometer
L_a	Laminated glass type
LCA	Life-cycle assessment
NRPE	Non-renewable primary energy
OD	Ozone layer depletion
PVB	Polyynyl butyral interlayer
PVC	Polyvinyl chloride frame
PVC.D	PVC frame for double-glazing

PVC.S	PVC frame for single-glazing
PVC.T	PVC frame for triple-glazing
S	Single-glazing
SA	Single A glazing solution
SB	Single B glazing solution
t	ton
T	Triple-glazing
TA	Triple A glazing solution
TB	Triple B glazing solution
T_e	Tempered glass type
U	Thermal transmittance value
WOO	Wood frame
WOO.SDT	Wood frame for single-, double- and triple-glazing
$\succ$	dominates
$\forall$	for all
$\exists$	there exists
$\wedge$	and