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Analysing the environmental impact of windows: A review

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ABSTRACT

Windows have a major influence on indoor comfort and are critical factors in terms of the energy consumption of buildings. Accordingly, the design and performance of window glazing and frames are key elements in the implementation of thermal regulations and contribute to the success of energy renovation policies. However, despite their multifaceted-role, there is a lack of holistic studies that bring together the environmental issues resulting from the production, use and disposal of windows. The aim of this article is to review these multiple aspects holistically and to provide a better understanding of the role that windows can play in reducing the environmental impact of buildings.

As such, this paper analyses twenty-three environmental studies of windows, frames and glazing, including recent Environmental Product Declarations. It is the first study to address environmental issues related to windows from a holistic perspective considering both quantitative and qualitative studies. Through this approach, this paper outlines the methodological issues associated with the environmental analysis of windows, particularly regarding the definition of the functional unit and the quantification of impact during the use phase. Additionally, this review provides new insights into the life cycle of windows, frames and glazing by comparing the results of research carried out since 2000. The paper also defines important questions pertaining to the understudied area of the end-of-life of windows and their recyclability and reusability.

Finally, this paper takes advantage of the complementarity of the reviewed studies to discuss three propositions that would support the development of an improved framework that would be suitable for the life cycle assessment of individual building elements such as windows, where energy efficiency depends both on the behaviour of occupants as well as on the rest of the energy systems of a building.

1. Introduction

The extraction, transportation and transformation of the considerable volume of materials[1] needed for our built environment has a major impact on the entire biosphere [2]. The building sector alone consumes a large part of these flows, a considerable proportion of which is used to provide indoor comfort in buildings. Buildings account for 54% of the global final-electricity demand and 23% of global energy-related CO_2 emissions[2] in 2014 [3].

While this environmental impact has increased since the post-war period, windows have become an emblematic architectural element and their technological development has aimed at serving somewhat the contradictory ambitions of combining energy efficiency with the ideals of modernity, i.e. transparency and comfort [4]. Nonetheless, as a result of rising standards in terms of energy efficiency since the 1970s, increasing attention has been paid to glazing and frames and the role they can play in reducing the environmental impact of a building.

Windows represent a significant material flow with an estimated consumption of 73.2 million units[3] in 2012 throughout the 27 Member States (MS) of the European Union (EU) [5]. Because of their transparency they are a key element of the energy systems of buildings [6,7], with a considerable impact on thermal, visual and acoustic comfort. Thus, the appropriate design of windows in new buildings is essential for reducing the energy consumption related to lighting and HVAC. This challenge is even greater in old buildings with ageing components that do not meet current standards. In 2011, windows-in-use represented

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[1] E.g. the consumption of sand and gravel which reached 28.6 Gt/yr in 2010 [1].

[2] Upstream electricity generation included.

[3] A unit represents 1.3 m × 1.3 m.

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nearly 5783 million square metres in Europe [5], equivalent to more than 4322 million units with 70% estimated to be at least 20 years old [8].

Accordingly, given the importance of this flow and stock and considering the role that windows play in the energy consumption of buildings, many studies have been carried out since the late 1990s in order to assess their environmental impact mainly in the form of a life cycle assessment (LCA). However, these studies have either been limited to specific aspects relating to the life cycle of windows or are already out of date. In fact, there is a lack of holistic studies that bring together the environmental issues resulting from the production, the use and the disposal of windows, and it is important to establish a state-of-the-art picture of this scientific knowledge. This is particularly significant, given that fact that thermal regulations in the EU have been strengthened and the industry has been producing increasingly high-performance products in recent decades, all with the aim of improving the energy efficiency of buildings [9]. However, the production of new windows inevitably impacts the biosphere, and the significant increases in thermal renovation practices have turned a lot more existing glazing and frames into waste. Thus, the general objective of this study is to holistically review the multifaceted aspects of the environmental footprint of windows and to provide a better understanding of the role that glazing and frames can play in reducing the environmental impact of buildings. More specifically, it aims to:

i) Generate insights into the life cycle of windows, frames and glazing by comparing the results of studies carried out since 2000.
ii) Analyse the methodological issues associated with the environmental analysis of windows, particularly regarding the definition of the functional unit and the quantification of impacts during the use phase.
iii) Identify unresolved questions around the end-of-life of windows, their recyclability and reusability.
iv) Define paths towards the development of an appropriate framework for the LCA of individual elements such as windows that are dependent on the behaviour of occupants and on the rest of the energy systems of a building.

These objectives require a thorough review of the methods used to carry out an environmental analysis of windows, glazing and frames and this paper proposes the innovative approach of doing so from a holistic perspective. A series of studies have been gathered on the basis of the broad definition of “environmental impact” given by ISO14001.[4] This study considers both quantitative and qualitative studies, and in this way links studies that were previously isolated from each other. This approach allows us to include not only the many LCAs that have been carried out, but also research projects which have addressed issues such as financial costs [10,11], lifespan and weathering performances [12,13], and comfort issues [14]. Through this perspective we explore the complementarities, contradictions and possible gaps in the methods that have been thus far implemented to assess the environmental footprint of windows.

In total, twenty-three publications and twenty-one Environmental Product Declarations (EPD) were analysed using a reading grid. The following section (2) explains how these studies were selected and the method used to review them. Then, section 3 analyses their goals and scopes while highlighting the methodological issues related to the LCA of a window. Issues related to the definition of the functional unit are considered (3.1) followed by an outline of the methods used to analyse the production and use phases (3.2) and the end-of-life of windows (3.3). Section 4 summarises the key results of the reviewed papers per life stage (production 4.1, use 4.2, end-of-life 4.3) and concludes by presenting the main findings regarding the global life cycle of windows (4.4).

Finally, the last section (5) addresses designers, industrial companies and researchers, identifying the main issues that remain to be clarified. First of all, we discuss data and model uncertainties, as well as sensitivity analyses regarding occupants' behaviour (5.1). Then, we define work paths towards an improved framework for a more robust methodology (5.2). Finally, we highlight the research that is still needed on the way in which window design guides environmental practices (5.3).

2. Material and methods

Firstly, the term window as used in this article is defined (2.1). Then (2.2), the method used to select the reviewed papers is described. Finally (2.3), the analytical grid built to review these selected studies is presented.

2.1. Definition of the subject of study

In this article, a window is understood as an element of a facade that consists of at least one glazing and one frame, and which may also include a shading device. These components are characterised by a very strong, interdependent relationship which raises a fundamental issue for environmental analysis, highlighted by Chevalier et al. [15]: “if the glazing and the frame (but also the gasket, handles, etc.) are distinct products but the functional performance is ensured by the window, is it possible to analyse the components individually? Or is an LCA only achievable on the final system that assembles them?”

When examining the literature, it is clear that there are two main approaches:

- Some authors focus their analysis on a single element, most often defining the rest of the window according to simplified assumptions. The majority of studies take window frames as their sole subject of study [10,12,13,16–22], while a few examine glazing [23–25] or shading devices [11,26,27] only.
- A second approach considers windows as a whole, including the glazing and the frame [8,14,20,28–33] and sometimes including shading devices [34].

It is important to consider these approaches as complementary: each specific element contributes to a better understanding of the environmental issues at stake. Therefore, this review focuses on windows but also on its two main components taken separately, i.e. frame and glazing.

2.2. Material: selection of papers

An environmental analysis carried out at the scale of a product is most often based on LCA principles, whose methodological framework is now well defined [35,36]. Numerous publications have recently adapted the method to address issues specific to the built environment and, more specifically, to buildings [2,37].

However, the environmental analysis of windows undertaken in recent years is not limited to LCAs. Some authors have opted for a qualitative approach [14,29,38], with a few advocating a holistic perspective [32] in order to question the use, durability, weather resistance and service life of glazing and frames. In addition, an increasing number of research projects combine environmental and economic analyses in order to calculate the ecological and financial payback period [8,10,11,30,33]. All of these approaches are mutually enriching and allow for a better assessment of the flows of resources and their

[4] According to ISO 14001:2015, an environmental impact is a “change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects.” The environment is the “surroundings in which an organization operates, including air, water, land, natural resources, flora, fauna, humans, and their interrelation.”

environmental impact through an enhanced understanding of technical, social, and economic constraints. For this reason, we have included both quantitative and qualitative studies, thereby leading to a survey of thirty-six scientific publications.[5] In order to limit this number of publications and ensure their relevance, four criteria were defined:

- Impact indicators: quantitative analyses had to consider at least embodied energy, whereas qualitative research had to focus on issues related to assumptions made during an LCA.
- Scientific value: reports from industrial companies without clear evidence of the authors' independence were dismissed.
- Geographical area: this review focuses on Western Europe as this region constitutes a single market which is relatively homogeneous in terms of industrial structure and environmental regulations. However, non-European publications may be taken into account if their conclusions are relevant to Europe (i.e. similar processes, climates, economic systems and calculation standards).
- Language: preference was given to English-language publications although a doctoral dissertation and several EPDs written in French were included as the results were considered relevant.

A fifth criterion relating to the publication date was also defined. Only studies published since 2000 were reviewed in order to provide an overview of the current state of research and to consider a range of up-to-date products. This decision was taken despite the review of LCAs of windows published in 2008 by Salazar and Sowlati [39] because they focus mainly on results rather than on methods and consider only LCAs, even though some authors in their study extended their analysis through life cycle cost (LCC) or used statistical studies to discuss maintenance and lifespan issues. These papers are all included in our review.

In the end, 16 papers, 6 reports, 1 doctoral thesis and 26 EPDs were selected and analysed using a reading grid which is presented in the following section.[6]

2.3. Analysis grid

In order to systematise the analysis of the publications, a reading grid was established based on questions focusing on goals and scopes:

- What is the goal of the research?
- What is the functional unit used, i.e. what are the "performance requirements that the product system fulfils[7]"?
- How is the lifespan of the product defined?
- What properties and functions of the product are considered?
- Which life cycle phases are analysed?
- What building types, constructive systems and materials are considered?
- What is the geographical area under consideration?

A second set of questions deals with methods and assumptions, i.e. the steps, tools, standards adopted in each study and the main hypotheses highlighted. The final set of questions considers the indicators used to assess the environmental impact and questions the generation and use of the data.

The results of this analysis are summarised in Table 1. The studies reviewed are classified by year, with a few being grouped by author as their publications are based on the same research project. This table presents the answers to five of the questions previously outlined and thus provides the key elements for understanding the problem statement and scope of each of these studies: purpose, location, functional unit, lifespan, standards, main methodological approach.

3. Goals, scopes and methods: where to draw boundaries when analysing windows?

In this section, the different approaches used to carry out the environmental analyses are reviewed. Firstly (3.1), we discuss the strategies used to define the relationship between the frame and the glazing, as well as between the window and the rest of the building. Secondly (3.2), five types of methods used to assess the ecological impacts are identified and discussed. Lastly (3.3), a series of fundamental assumptions about the end-of-life of windows are examined.

3.1. Interdependence issues

First of all, as part of a building's energy system, windows are strongly linked to HVAC devices as well as to the rest of the façade [41]. To carry out an environmental assessment, these links have to be defined through a series of assumptions that determine the part played by a window within the total energy consumption of a building. Moreover, this system must consider the occupants as they are in constant interaction with the building, e.g. adjusting the temperature, opening and closing windows, raising and lowering blinds [42].

Secondly, windows have functions that cannot be summarised by using an energy-based system; they also provide weather-tightness, privacy, acoustic and visual comfort, daylight and a feeling of openness [15]. Therefore, an environmental analysis of such an element is not only about tracking energy and material flows over a certain lifetime, but it is also about providing a model that reflects the complexity of the social-ecological system of a building [43].

Finally, such issues raise the question of where to draw the boundaries when analysing a window, and, how should we assess the role it assumes in terms of the environmental impact of a building during its use phase? The answers have important implications, and for this reason, the definition of the role of such an interwoven element is an essential step.

ENTEC [18] carried out the only LCA from cradle to grave that considers a single component, i.e. the frame. Three other publications only look at glazing but do so because they do not include the energy consumption resulting from the use phase [23–25]. Apart from these four papers, the majority of authors consider a window as the functional unit even when the analysis aims to compare different types of frame or of glazing. Therefore, they solve the problem of interdependence between components by considering the window as a whole and then varying the technical characteristics of the element under study, i.e. the glazing or the frame. The goal of the research determines the approach, which can be grouped into three main categories:

- A few authors do not take the use phase into consideration, framing their analysis from cradle to gate. Their goal is to provide data about a specific product: timber frame [21], electrochromic glazing [24]. This is particularly the case for EPDs [44–51].
- Another strategy regarding the use phase consists of focusing exclusively on maintenance operations. The goal of these studies is either to compare frame materials [10,12,16,20] or to highlight the

[5] A first keywords query on the search engine of the Université Libre de Bruxelles (https://cibleplus.ulb.ac.be) resulted in a list of publications for which bibliographies were reviewed to broaden the scope. Lastly, research on the websites of the main industrial associations of the sector (e.g. Glass for Europe, the European Aluminium Association) has enabled the list of reviewed studies to be supplemented by a few reports.

[6] The list of the thirteen publications which are excluded can be found in the appendix, together with the reasons for their rejection. These publications represent a combination of scattered sources, which are often too old or which are not coherent in terms of the topics they cover. Regarding EPDs, the only reason for the rejection is the lack of external verification.

[7] We refer to the definition of the functional unit given on the website Consequential-LCA (2015). Defining the functional unit. www.consequential-lca.org (accessed October 26, 2018).

Table 1
Summary presentation of selected studies (1/3).

#	Studies	Purpose	Location	Functional unit	Lifespan	LCA standards	Main methodological approach
1	Entec 2000 [18]	Comparing PVC and wooden frames	UK	mass of frame needed for a 1.2 × 1.2 m window	30 y.	no information	LCA. Energy consumption during the use phase calculated as a function of the heat transfer coefficient of the frame, Uf
2	Citherlet et al. 2000 [34]	Comparing different window configurations in three European climates	UK, CH, IT	1 m^2 w/shading system	Aluminium, wood–aluminium frames: 45 y. PVC, and wood: 30 y.	no information	LCA. Energy consumption during the use phase calculated as a function of the heat transfer coefficient of the window, Uw, including ventilation
3	Bodart 2002 [23]	Comparing nine types of glazing for office buildings	BE	1 m^2 of glazing	20 y.	no information	Life cycle energy assessment (LCEA). Calculation of energy consumption during the use phase, including heating, cooling, and lighting
4	Asif et al. 2002, 2005 [12,16]	Comparing the environmental impact of frame materials, and assessing their weathering performances and lifespans	EU	a 1.2 × 1.2m^2 window	subject of the research	no information	Combines an LCA mainly focused on energy and Global Warming Potential (GWP) with weathering performance tests and a survey assessing effective lifespans
5	Menzies and Wherrett 2003, 2005a, 2005b [14,29,30]	Understanding the role of environmental issues in the design process; assessing impacts of windows on near and far environments	UK	Per cubic meter of building	n/a	no information	Sociological survey (focus groups, interviews and post-occupancy surveys), LCA, LCC (cradle-to-gate, use phase included for heating and cooling costs)
6	PE Europe et al. 2004 [40]	Reviewing published LCAs of PVC and different materials	EU	n/a, review	n/a	ISO 14040	A literature review of studies published between 1994 and 2000
7	Kiani 2005 [31]	Comparing environmental performance of curtain walls according to different energy properties of the glazing	UK	a 1.2 × 1.2 m^2 window	20 to 25 y.	ISO 14040:1997	LCEA. Thermal modelling to calculate heating and cooling loads according to different transmittance, reflectance, and absorbency. Two end-of-life scenarios assessed
8	Syrrakou et al. 2005 [24]	Assessing the embodied energy of an electrochromic glazing, cradle-to-gate	EU	40 × 40 cm^2 of electrochromic glass	n/a	ISO 14040	An LCA by the book in four steps according to ISO recommendations, considers only energy
9	Baldasano et al. 2005 [17]	Comparing different frame materials (PVC, aluminium, and wood)	SP	a 1.34 × 1.34 m^2 window	50 y.	no information	LCA (energy and GWP). Energy consumption during the use phase assessed through the thermal modelling of a room (w/Uw and air permeability). 3 climates and different recycling rates considered
10	Salazar and Sowlati 2008a [20]	Comparing the environmental impact of window frames (aluminium-clad wood, PVC and fiberglass)	USA	a 0.6 × 1.2m^2 window	window:75 y. PVC: 18 y other materials: 25 y	ISO 14040	LCA. Four steps according to ISO. The assessment of the use stage includes only maintenance needs (sealed unit replacements and recaulking). Impacts grouped and scaled based on IMPACT 2002
11	Salazar and Sowlati 2008b [39]	Reviewing published LCAs of windows	n/a	n/a	n/a	n/a	Review of studies published to date. Two main approaches highlighted: specific processes directly related to the frame material; and energy payback comparison according to thermal properties
12	Tarantini et al. 2011 [22]	Comparing different frame materials (timber, aluminium and PVC)	IT	a 1.2 × 1.3 m^2 window	30 y.	no information	LCA. Comparative analysis considering the impact of thermal transmittance, air tightness and solar factors on the heating loads
13	Sinha and Kutnar 2012 [21]	Comparing different frame materials (wood, PVC and aluminium), cradle-to-gate	CH and DE	1 m^2 of window	n/a	ISO 14044	LCA (energy + GWP). Design of 3 windows, calculation of their thermal properties, assessment of their carbon footprints
14	Menzies 2013 [10]	Comparing different types of frames (timber, modified timber and aluminium-clad timber)	UK	a 1.23 × 1.48 m^2 window	bldg: 60, 80 or 100 y timber: 56–65 y; acetylated wood: 68-80 y. al-clad timber: 71–83 y.	ISO 14040 PAS2050	Whole Life Costing (WLC), Service Life Planning (SLP), and LCA. Uncertainties: different assumptions regarding lifespan, climate conditions, end-of-life scenarios, and carbon intensity electricity grid. Use phase: only maintenance is considered
15	Babaizadeh and Hassan 2013 [25]	Assessing the environmental impact of nano-sized titanium dioxide coating on glass	USA	1m^2 of titanium dioxide coated glass	40 y.	ISO 14040 ASTM, LCC method	Comparative LCA from cradle to grave of uncoated and coated glass. Assessment of the purification potential during the use phase. Includes economic analysis
16	Baldinelli et al. 2014 [32]	Assessing the environmental performance of a wooden window	IT	a 1.23 × 1.48 m^2 window	30 y.	ISO 14040/44	Analysis of a real window: measurement of thermal transmittance, sound insulation, air and water tightness, and wind load resistance. Comparative LCA w/2 optimised designs (solar control, warm edge spacer)
17	Institut für Fenstertechnik et al. 2015 [8]	Comparing different combinations of glazing and frames	EU	a 1.3 × 1.5 m^2 window	40 y.	ISO 14040/44	Standard window with a hybrid frame composition defined according to the consumption rates of the 3 main materials:

(*continued on next page*)

Table 1 (*continued*)

#	Studies	Purpose	Location	Functional unit	Lifespan	LCA standards	Main methodological approach
							PVC, wood, aluminium. Comparative LCA and LCC according to the energy performance (U value, solar factor, air leakage)
18	Minne et al. 2015 [33]	Assessing the influence of climate on LCAs and LCCs of windows (from single to triple-glazed, w/aluminium-clad wood, PVC, and fiberglass)	USA	a 1 ft^2 window	30 y.	ISO 14040/ 44:2006	LCA and LCC. 17 different climates: calculation of energy consumption during the use phase according to U values and solar factors
19	Mösle et al. 2015 [19]	Comparing different frame materials (aluminium, timber, timber-aluminium and PVC)	EU, Berlin and Rome	a 3.75 m^2 residential window, a 14 m^2 curtain wall	building: 50 y PVC: 30 y; alum. and alum-clad wood: 50 y. timber: 30 y. (residential) and 40 y (office)	ISO 15686-5 ISO 14040 EN 158042	LCA. Energy consumption over the use phase calculated according to U values and solar factors, using thermal simulation software
20	Carlisle and Friedlander 2016 [13]	Comparing different frame materials according to different lifespan and end-of-life scenarios (aluminium, timber, timber-aluminium and PVC)	USA	the frame required to produce 1 m^2 of visible glazing	building: 80 y. frames: various scenarios	ISO 21930 ISO 14040/44	LCA. Comparative analysis according to different maintenance and replacement regimes with the creation of secondary frame types: resealed, recoated, hardware replaced. Service life: 3 scenarios defined according to the lifespan and maintenance. Recycling: recycled content and end-of-life recycling methods

importance of assumptions and modelling practice related to maintenance and end-of-life [13].

- A third group of authors takes into account the influence of glazing [23,31,32], frames [17,18,22] or windows [8,30,33,34] on energy consumption. Their goal is to compare different designs through the calculation of energy use, environmental impact such as global warming potential (GWP) and/or financial payback periods.

All of these strategies are based on life-cycle thinking but may also include other types of analysis to enrich the LCA in order to more broadly address the impact of windows during the use phase.

3.2. Methods applied in the studies

Most of the studies reviewed [35,52] were conducted in accordance with ISO standards [35]. Some do not indicate any norms, but from 2010 onwards, one can clearly see the influence of improved standards and of the publication of handbooks [36]. Today, almost every LCA follows a four-step framework: (a) LCA goal & scope definition, (b) Inventory analysis, (c) Impact assessment, (d) Interpretation.

Across all of the studies reviewed, the analysis of the production and transportation phases raised no significant issues in following these steps. Data was usually collected through a literature review of journal papers and reports, some coming from industrial companies and databases (mainly Ecoinvent and GaBi). By relying on past research or by modelling the trajectory and transformations that lead to the final product, the studies assessed impacts from cradle to gate quite easily. This was particularly the case for EPDs, which rarely looked beyond this stage.

However, the methodology defined through ISO standards is not sufficient once the studied product has been integrated into a complex system where its role depends on other elements. As discussed previously (3.1), this is precisely the case with windows whose impact is easy to assess over the production phase but much more difficult to track once installed in an edifice. Indeed, it becomes difficult to quantify their contribution to a building's environmental footprint, the latter being the result of the use of a space defined by a large number of elements that constitute its energy system. Such an analysis involves making assumptions and defining a protocol to model maintenance, replacement operations, and energy transfers. Table 2 presents the three strategies that have been identified by the studies covered in this review.

One approach (type a) uses quantitative approaches to assess the contribution of windows to the energy consumption of a building. Some studies focuses on the glazing or on the frame while others combine these elements in one functional unit (which sometimes include the solar shadings [34]). The studies also differ regarding the comprehensiveness of the quantitative analysis. For example ENTEC [18] limits the study to a single component and only assesses its performance by analysing its thermal conductivity. Obviously, such an approach will not allow for a proper evaluation of the impact of a window design on the energy consumption of a building, as it clearly neglects the radiative part of heat flows through glazing. Baldinelli et al. [32] offer a far more comprehensive and reliable evaluation of the thermal, acoustic, optical, mechanical and environmental performance of windows based on actual measurements. It comes clear that measurements and simulations are two complementary approaches, the first assessing the actual properties of the component while the second estimates its impact based on these properties. Such a combination makes quantitative approaches promising, although it faces three major difficulties:

1. The acquisition of empirical data is technically complex. For this reason, manufacturers' documentation of a product's expected properties often become the prime sources of data but these rely on analyses conducted in controlled environments and therefore may miss certain key aspects regarding the impact of windows on energy

Table 2
Methodologies for the environmental analysis of windows during the use phase.

Type	Approach regarding the use phase	Studies
a	Quantitative analysis of alternative design options	Frame only: Baldasano et al. 2005 [17]; Tarantini et al. 2011 [22] Glazing only: Baldinelli et al. 2014 [32]; Bodart 2002 [23]; Kiani 2005 [31] Combined: ENTEC 2000 [18]; Citherlet et al. 2000 [34]; Institut für Fenstertechnik et al. 2015 [8]; Minne et al., 2015 [33]; Menzies and Wherrett, 2005b [30]
b	Combines quantitative and qualitative analysis of alternative design options	Asif et al. 2005, 2002 [12,16]; Menzies and Wherrett, 2005a, 2003 [14,29]
c	Only considers maintenance	Carlisle and Friedlander 2016 [13]; Menzies 2013 [10]; Salazar and Sowlati 2008a [20]

consumption, e.g. the airtightness.

2. Thermal models do not easily allow us to consider complex interactions related to windows, such as the impact of glare or direct radiation on the occupants' behaviour, or the opening and closing of windows or blinds.[8]
3. Partly as a consequence of the previous difficulty identified, thermal models used in LCA analysis might be oversimplified. For example, a few authors only took energy consumption related to heating and cooling into account even though the window parameters have a significant influence on electricity consumption from the use of artificial lighting [8,30,33]. Fenstertechnik et al. [8] state that "there is currently no universally agreed method to directly translate changes in window light transmittance to changes in energy consumption by building lighting systems"; they refer to a simplified method in ISO 18292 to include a daylight potential factor without a clear explanation on how to evaluate its influence on energy needs.[9]

A second approach (type b) uses qualitative analyses which are used to produce statistical data on window use. The complementarity of these approaches with quantitative evaluations is particularly obvious when they allow a better understanding of the key hypothesis of LCA evaluations. For instance, in order to assess the effective service life of windows and their maintenance needs, the study carried out by Asif et al. [12,16] combines an LCA with an assessment of the weathering performance of different frame materials and a survey conducted among public authorities throughout the UK. It is clear that this type of approach improves our understanding of the environmental impact of windows and provides essential knowledge on the definition of certain assumptions for an LCA, such as the lifespan (see 3.3) or the influence of windows on occupant's satisfaction and behaviour.

However, these studies do not develop the method to include this knowledge on certain assumptions for an LCA and therefore stress the difficulties mentioned when discussing quantitative approaches. Also, it should be underlined that these qualitative evaluations do not allow us to draw conclusions on the questions addressed by LCA methods such as the selection of alternative design strategies. This is because comments obtained from users relate only to specific situations whereas a full and comprehensive interpretation requires extended surveys combined with comprehensive statistical analysis. Moreover, given the many parameters that comprise the built environment, it is often difficult to identify the relationship between the user's perception and the window's design in a meaningful way.

The discussion of both approaches highlights the complexity of assessing the multiple impacts of windows during the use phase. It shows that both qualitative and quantitative studies of the use phase are difficult to include in the LCA of a window. This might explain why a last group of publications (type c) bypasses the difficulty of assessing the contribution of a window to the energy consumption of a building by limiting the study of the use phase to maintenance and replacement processes. These authors pay more attention to the service life of the elements studied, such as Menzies [10] who enhanced her LCA by adding a whole-life-costing (WLC) study and an assessment of the lifespan of different windows using the service-life-planning[10] (SLP) method. These authors have demonstrated the strong influence of assumptions regarding the service life of glazing, frames, and windows.

In view of these three approaches, we might conclude that there is neither a comprehensive framework nor a consolidated method available for the proper evaluation of the use phase for elements such as windows. This complexity lies in the fact that windows influence energy consumption in multiple ways, interacting with other elements of the building systems whilst also having an impact on the occupants' satisfaction and thus their behaviour.

3.3. Defining the lifespan: a key assumption

The period of time considered in an LCA has a considerable influence on its results. It determines the frequency of maintenance operations, the number of replacements and the moment when the use phase ends, followed by the end-of-life management processes. These considerations are addressed on three levels:

- The lifespan of the window studied.
- The lifespan of its components: frame, glazing, gaskets, assembly and possibly its opening systems. Will these elements need to be replaced? Is it economically feasible to do so? If not, will the window be able to provide the same functions at the same level of performance despite the degradation of some of its components?
- The lifespan of the building: will the windows have to be replaced during the life of the edifice or will they still be fully functional if they are scrapped due to the renovation or destruction of the building?

Only a few authors address these issues even though these hypotheses have a significant impact on the results of an LCA. Nevertheless, we review the main strategies adopted to integrate lifespan into the assessment of the environmental impact of windows.

The lifespan of windows is estimated to be between 30 [32,33] and 40 [8] years whereas that of frames (PVC, aluminium and wood) ranges from 30 [17] to 50 years [18,22]. For glazing, Bodart [23] defines the lifespan as 20 years. In his study on curtain walls, Kiani [31] considers leaseholds (20–25 y) as determinants of the time frame. This is an interesting approach which seeks to consider the reality of commercial buildings where renovations are frequent, often scrapping glazing that is sometimes still functional. Salazar and Sowlati [20] choose a long

[8] Although advanced modelling environments and research progress might mitigate this difficulty in years to come, software development will not necessarily make the evaluation easier since more comprehensive models will probably need larger sets of hypotheses. See for example recent developments concerning energy simulations of adaptive thermal comfort [53,54].

[9] This limitation might be overcome by the use of coupled lighting and thermal simulation on case studies, stressing the above mentioned difficulties that accompany advanced modelling strategies.

[10] Defined according to ISO 15686, an SLP provides a process for estimating the service life of a building, a constructed work, or components. "Its purpose is to give a structured response to establishing normal service life from a reference or estimated service life framework." [10].

lifespan (75 years) in order to investigate issues related to the maintenance and replacement of frames which do not last as long, e.g. the service life of aluminium-clad wood and fiberglass frames is 25 years while that of PVC products is only 18 years because “the PVC windows installed in North America are typically the lowest cost option and are commonly replaced for poor performance such as binding and allowing air and water infiltration.”

However, these studies give little or no justification for the lifespan considered despite the crucial importance of this assumption, thereby somewhat weakening their conclusions. Nonetheless, three publications do directly address the question of lifespan. As discussed previously (3.2), Asif et al. carried out a survey in order to assess the effective service life of different frames. Their study confirms the longevity of aluminium (43.6 years), which performs well in combination with wood, demonstrating both durability and ease of maintenance (46.7 years). When used alone, wood is quite demanding in terms of preservation but can have a lifespan of almost 40 years (39.6 years) if regular maintenance is carried out. Finally, their results point out the short service life of PVC frames (24.1 years), which are also complicated to repair.

In her detailed SLP study (see 3.2), Menzies gives strong arguments to back up her estimation of the service life of wooden frames (56–65 years), acetylated timber (68–80 years) and aluminium-clad timber (71–83 years). More recently, Carlisle and Friedlander [13] have completed a comparative analysis of different frames for the US market with the aim of determining “the impact of end-of-life modelling practice on LCA results.” In order to do this, they consider a lifespan of 80 years and define a series of maintenance levels (little to none, low and high) and replacement regimes (resealing, recoating, and hardware replacement) as well as three different lifespans (warranty period, long and short).

Carlisle and Friedlander emphasise the strong influence of assumptions regarding the end-of-life of such products. For instance, their results show that for aluminium frames, better maintenance and a longer service life (80 years instead of 20 years) lead to a decrease of nearly 52% in GWP and of around 45% in the impact associated with the depletion of fossil fuels. According to the authors, “expectations of service life proved to be the most important factor in considering environmental impact of frame materials”. Although this study does not consider the energy consumption of a building, the conclusion highlights the need to discuss and analyse uncertainties and variabilities according to different use and end-of-life scenarios.

4. A review of environmental impacts of windows throughout their life cycle

In this section, we present the main results indicated in the publications reviewed. The purpose is to summarise the ecological impacts of windows by phase, i.e. production (4.1), use (4.2) and end-of-life (4.3), before highlighting the main findings concerning the whole life of windows, frames and glazing (4.4).

4.1. Production phase

The production phase includes the extraction, transport and processing of raw materials in a so-called “cradle-to-gate" approach. The flows of energy and materials required to produce glazing and frames are substantial and have a considerable impact on the biosphere.

The first material we focus on is glass, examining the results of a series of EPDs published for the Western European market [55–58]. Fig. 1 shows the greenhouse gas emissions and water consumption resulting from the production of 1 kg of glass, including specific data for the three stages with the largest contribution.

As glass is mainly composed of sand and sodium carbonate, most of the greenhouse gases (GHG) are emitted during the melting of these raw materials with the rest of the glass batch in gas-fired furnaces (almost 60%, see Fig. 1). However, the production of sodium carbonate through the Solvay's chemical process accounts for nearly a quarter of these emissions and, in addition, requires a significant amount of water, i.e. just over half of the 22 litres consumed to obtain 1 kg of glass. By weight silica sand is the most important material in the manufacture of glass, equalling just over half of the total mass of the raw materials required. In 2011 world production of silica sand was estimated at 135 million tonnes and by 2012, this had risen to 140 million tonnes; 31% was used by float glass industries (automotive glass included) [59].

Nevertheless, a sheet of glass is rarely used as it is and industries generally seek to improve its mechanical or thermal properties, ultimately leading to additional environmental impacts associated with the production processes. Fig. 2 illustrates this variation through a comparison of different glazed products according to a large variety of ecological indicators. It is worth noting that the processes of strengthening the mechanical properties of glass (heat toughened and laminated) increase the ecological impact, whereas the addition of a coating is not particularly significant except for the magnetron deposition technique regarding ODP and ADP.

Once glass panes have been produced, the assembly of an insulating glass unit (IGU) requires the use of spacers and seals, which have a relatively small environmental footprint as they account for less than 2% of the bill of quantities of a window. However, infill gases used to improve thermal performance can significantly increase the embodied energy of an IGU. This is especially true in the case of krypton which has an estimated embodied energy of about 460 MJ for a double-glazed window of $1.2 \times 1.2\,m^2$, compared to 0.011 MJ for argon and 0 MJ for air [31]. This impact greatly lengthens the payback period despite the better thermal performance of krypton glazing [30].

Concerning frame materials, results are less consistent. While one study suggests that PVC, aluminium clad wood and fiberglass have a substantially similar impacts in the North American market [20], others focused on Western Europe emphasise the very high environmental footprint of plastic frames which consume three times more coal and oil than timber, and emit seven times more GHGs through the production processes of raw materials [18]. In contrast, two cradle-to-gate analyses [16,21] confirm the low impact wood has on the environment, which has the lowest values regarding embodied energy, GWP and acidification potential (AP), even though carbon storage potential is not included. According to these studies, aluminium is the least impacting on the biosphere, but this result must be tempered by the fact that its recycling potential has not been considered.

The production of assembly products (EPDM, silicone) is almost negligible given their weight in the bill of materials [60]. However, the stage of assembly in making the window contributes significantly to its environmental footprint. According to the EPDs reviewed, the assembly (i.e. the manufacturing of the IGU, window, and fittings components) represents between 10% of the GWP for aluminium windows with double glazing [61] and up to 45% for those made with PVC, thermal bars and triple glazing [62,63].

Finally, the impact of transportation and on-site assembly vary greatly depending on the mode of construction and the distance between the edifice and the manufacturing plant. However, it appears from the analysis of the EPDs that, on average, these two stages have a lower environmental impact, around (10^{-2}), than those accumulated from cradle to gate.

4.2. Use phase of windows

Once manufactured, transported and installed in a building, windows only generate relatively small flows of materials and energy. They have a negligible impact on indoor air quality as glass does not emit harmful particles, and emissions of plastic-based putty, mastics and sealants are in such small quantities that they are not a concern [64]. Maintenance requires the use of just under half a litre of cleaning solution per square metre per year with minimal ecological impact if

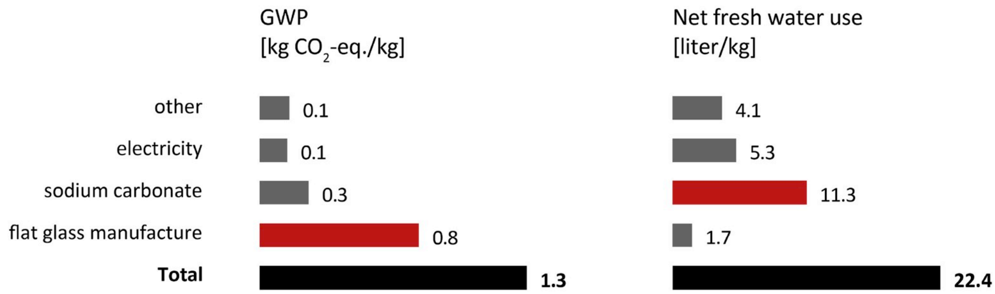

Fig. 1. GWP and net fresh water use for 1 kg of flat glass, from cradle to gate.
Source: [57].

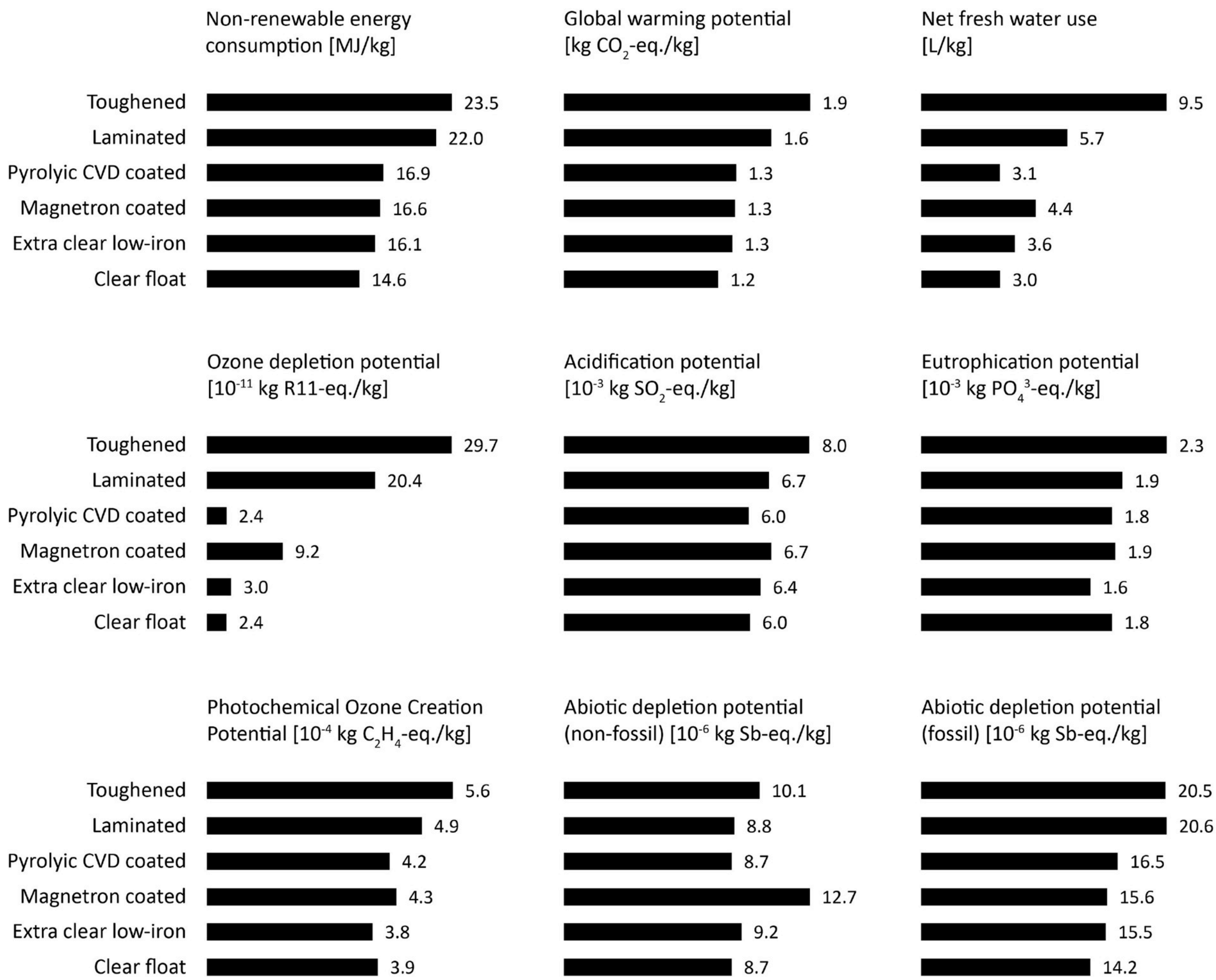

Fig. 2. Comparative analysis of different types of glass per kilogram.
Sources: [46–49,51,58]

products meet European environmental criteria. Seals are replaced every 10–15 years with no significant impact on the biosphere, standing in contrast to the impact of the production phase of a window. However, as discussed earlier (3.1), windows are involved in the management of large flows of energy through their role in the facade. Summarising the conclusions drawn by the authors who tried to quantify these impacts is a delicate task as their approaches and case studies are rather diverse, but the main lines of thinking, along with several contradictions, have been identified and are discussed below.

A first trend can be identified from the analysis of data provided by EPDs. As mentioned in the introduction, in a context of increasingly stringent European thermal regulations, new and ever more energy-efficient products are constantly being developed, but they are also more complex and more material-intensive. Through the analysis of the data from six EPDs of double and triple glazing produced by a European company, we highlight a direct relationship between the ecological impact of the production of windows and their thermal resistance. This situation is illustrated by Fig. 3, which shows that the environmental impact between double and triple glazing can vary by up to 175% according to four ecological indicators: non-renewable primary energy, GWP, abiotic depletion potential (non-fossil), and photochemical ozone creation potential. One can also note the strong influence of laminated glass on the ecological impact of an IGU.

Thereby, a correlation between the improvement of thermal performance and the increase of embodied impacts is observed. This raises a central question: to what extent does greater efficiency during the use

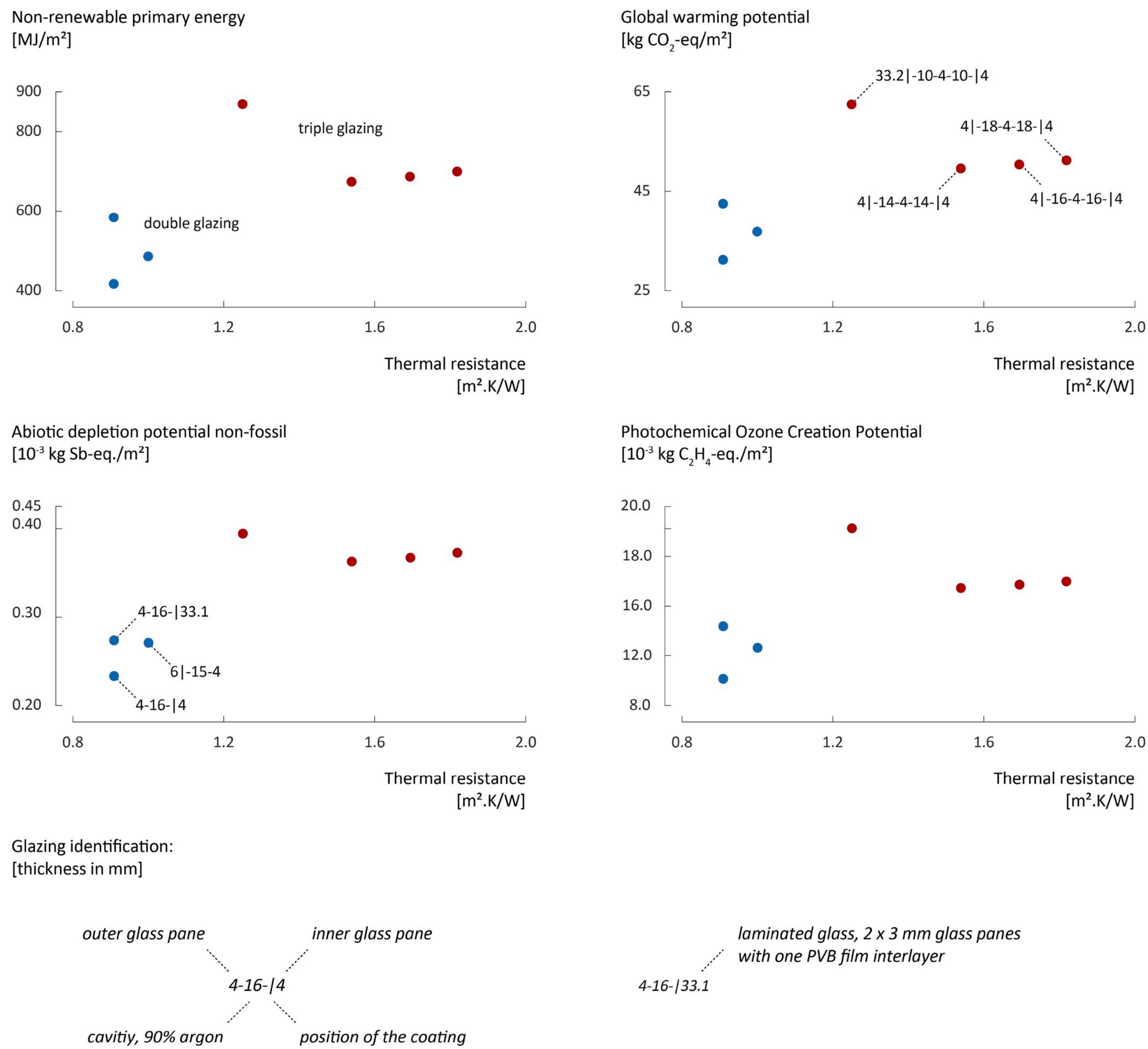

Fig. 3. From cradle to gate, study of four ecological indicators of different types of IGUs according to their thermal resistance.
Sources: EPDs from Saint-Gobain [44,45]

phase offset the greater ecological impact of the production phase? Many authors provide different answers to this question, each of which needs to be interpreted according to the scope of the study in question. For example, Kiani [31] demonstrates that for commercial buildings in London, the use of low-emissivity glazing reduces heating and cooling loads by more than 50%, thereby largely offsetting the increase in energy used to manufacture the curtain wall.

Accordingly, a reduction in GHG emissions of some 780 MtCO2/y would be possible if low-emissivity glazing were to become widespread in Europe [65]. However, this last study considers a baseline scenario that assumes a significant increase in the use of air conditioners in Europe and does not question the consequences of such a replacement plan in terms of waste management. In any case, the use of coated glass (low-e or solar control) has undeniable advantages in certain climatic conditions, depending on the orientation and use of the buildings. Thus, double glazing with reinforced insulation from argon and low-emissivity coatings combined with a frame with a thermal bridge breaker provides the best energy performance for residential use in cold and temperate European climates [8]. The same study also highlights the performance of triple glazing in this type of climate but underlines that the same analysis in hot climates leads to much less reliable results and with a greater change in relative ranking according to life cycle costs. However, it is important to note that this comparative analysis is based only on the primary energy consumption and does not consider any architectural designs or solar shading devices that might be installed.

4.3. *End-of-life of windows*

Decisions taken in terms of the management of glazing and frames at the end of their useful life have important consequences on the environmental footprint of windows. Disposing of these elements increases their environmental footprint, whilst the recovery and recycling of windows reduces the consumption of energy and raw materials through the production chain. For this reason, the scenario chosen for the modelling of this phase is crucial, while the conclusions that can be drawn and the decisions taken from an LCA strongly depend on the allocation method adopted regarding the potential for recycling or reuse [13,66].

Whilst IGUs from demolition and renovation sites most often end up in landfill (65%), a quarter of the glass from the IGUs is recovered to produce glass containers, glass wool or glass beads for technical use, with less than 10% being used to produce float glass again [67]. Similarly, polyvinyl butyral (PVB) and other kinds of reinforcing film for laminated glass are almost systematically sent to landfill [68].

In terms of frames, many scenarios are possible, depending on the material. Wood can be sent to landfill or prepared for energy valorisation, but the surface treatment they receive complicates their reuse[11] and recycling [8]. PVC is seldom reintegrated into production chains and most post-consumer waste ends up in landfill despite the high recyclability potential[12] of this plastic [40,70]. Some of the studies explain the low recycling rate as a consequence of the cost of the process, which is more expensive than the use of new raw materials [12,71]. For aluminium, the average content of recycled ingot used in the production of frames is at least 40% in Europe [60], although recovery rates of more than 95% are easily achieved on demolition sites [72]. Thus, windows and their components most often end up in landfill despite the fact that their recyclability is an important factor when considering how to reduce their ecological impact [13]. For instance, the recycling of PVC frames can save 2 tCO_2-eq./t of materials compared to that of virgin PVC resin—a result which relies heavily on distance and truck load, which can be bulky with a very low density [73].

However, integrating the use phase and the impact of thermal losses through windows inherently minimises the benefits of recycling. Baldasano et al. [17] indicate that the use of PVC or aluminium frames with a recycled content of 30% reduces the total GHG emissions by a marginal 1% over the entire life cycle of a window. Nevertheless, this study is based on a thermal simulation that assumes a high temperature setpoint of 22 °C all year long, thus strengthening the dominance of the use phase to the detriment of others.

Lastly, we can consider the reuse of windows as more or less anecdotal, partly because of the technical obsolescence of the products recovered, but also because of damage caused by disassembly and transportation [67]. Thus, while many initiatives in favour of recycling and reuse are taking place in the construction sector with stakeholders pushing for a circular economy, this review raises important questions regarding the management of windows at the end of their life (see section 5.3).

4.4. Overall assessment

This section presents the main results of the papers reviewed regarding the whole life cycle of windows, frames and glazing.

Through their meticulous investigation, Carlisle and Friedlander [13] highlight the impact of PVC window frames, noting that it is the most environmentally unfavourable option as they cannot be repaired and currently have very low recycling rate. Moreover, when recycling does in fact take place, the degradation of the material causes problems. These weaknesses are also pointed out by a series of studies [11,18,20], including Menzies [10] who emphasises that despite the claim that maintenance is not required, the degradation of PVC frames ultimately induces a shorter lifespan which heightens their ecological impact and their overall cost over a 60-year period.

Conversely, wood is the most demanding material for window frames in terms of maintenance but has significant potential in reducing GHG emissions under a long-life expectancy scenario [13]. ENTEC has calculated a reduction in waste generation of about 40% compared to PVC but stresses the fact that wooden windows need to be repainted regularly, which increases the potential formation of photochemical oxidant by 2.3 times more than plastic [18]. The option of pairing timber with aluminium provides a frame design that combines the low impact of wood with the strength of aluminium, thus being relatively easy to maintain. This option also has a potentially long service life with a good environmental performance in moderate and severe climate conditions [10].

Aluminium has strong resistance to external weather conditions, and if properly maintained and recycled, it could be considered the material with the lowest ecological impact [13]. However, its production uses a large amount of energy, meaning that its carbon footprint can only lowered if a significant proportion of recycled ingot is used [12,17,20,34]. Otherwise, aluminium could in fact be the worst option.

When the thermal performance of windows is taken into account, it appears that the main cause of impact on the biosphere is the combustion of fossil fuels for indoor climate control, regardless of the material chosen for the frame [17,22,34]. In general, authors agree that improvements in energy performance lead to a reduction in heating and cooling loads, which, in turn, offsets the increased ecological impact caused by the manufacture of a more complex product. This is a conclusion that has already been highlighted in the review carried out by Salazar and Sowlati [39]. One study evaluates the limit beyond which this assertion is no longer valid [8], and the authors conclude that triple-glazed windows could have a payback period that is too long in temperate and cold climates.

This study, like the others, uses a very simplified model of the socio-technical system of a building (see also section 3.2) and uncertainties and sensitivities are not discussed, even though a building and its occupants are a highly unpredictable object of study. The issue of the sensitivity of the results is obvious when the dispersion of the data is highlighted by the authors. For example, Tarantini et al. assess the weight of the production phase over the whole life cycle of a window and show that it can vary from 10% to 60% according to the climate and the environmental indicators considered [22].

5. Discussion

This section discusses the limits of the studies reviewed and highlights the need to recognise uncertainties in the data and in the models developed, as well as a need for sensitivity analyses in terms of occupants' behaviour (5.1). Then, it emphasises the importance of developing a methodological framework able to include social considerations into the assessment of the environmental footprint of windows (5.2). Lastly, it discusses the remaining questions concerning the end-of-life of windows (5.3).

5.1. A need to foster data and model uncertainties as well as sensitivity analyses related to occupant's behaviour

For many years, much work has focused on issues related to uncertainties in LCA [74–76] especially in the building sector where assumptions and data quality greatly influence the reliability of findings and, therefore, can lead to misinterpretations and a counterproductive decision-making process [77]. Although many calculation methods have been developed and integrated into the standards, these considerations have not received sufficient attention [78]. This is an observation confirmed by our review, i.e. little or no attention is paid to uncertainties while sensitivity analyses are rarely performed despite the wide spread of the values of the data.

To illustrate this issue, we have analysed several EPDs of glazed products and have gathered these results in the form of box plots

[11] In a recent study carried out in the south-east of Germany, the volume of recovered wood suitable for reuse was estimated at about 25%, of which 21% could be sent to other secondary sectors [69].

[12] However, high levels of lead have been measured in recycled PVC frames, with a rate that exceeds 0.1%, and must therefore be treated as a substance of very high concern (SVHC) in accordance to REACH [67].

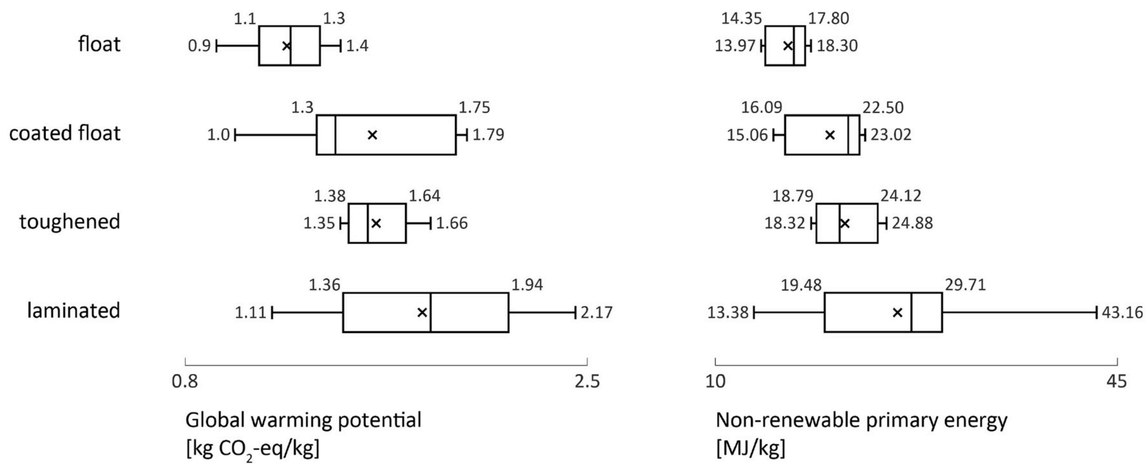

Fig. 4. One source of uncertainties is data dispersion as one can see above for different types of glass, from cradle to gate.
Sources: [46–51,55,56,58,79,80].

(Fig. 4). These graphs show the wide dispersion of the values provided by these studies: the ecological impact resulting from the production of different types of glass can vary by as much as twofold according to two indicators—GWP and non-renewable primary energy.

However, uncertainties related to data are not the only factors that require greater attention from researchers. To discuss this situation, we consider the five types of uncertainties specific to buildings, as defined by Kohler and Bodin [81]:

a) Data quality is seldom discussed, nor is information about the completeness of models. Only one paper [33] includes a calculation of values dispersion through a Monte Carlo simulation.
b) Building descriptions are inherently based on simplified assumptions that are barely called into question despite the wide use of building thermal models, which are highly sensitive to many factors such as thermal inertia or ventilation and heating systems [23].
c) The lifespan of windows and buildings are very important parameters, the influence of which is most often underestimated (see section 3.3).
d) The operation of windows and buildings is reduced to the heating and cooling setpoint temperature with no consideration given to the large variety of practices relating to indoor climate management and building maintenance [82].
e) The lifecycle of components is a major concern for the energy performance of windows, yet ageing and damaged seals and gaskets are never discussed even though they greatly impact thermal resistance and airtightness.

Thus, despite the high value of the information provided by the LCAs reviewed, they cannot claim to offer generalisable findings, particularly if an uncertainty and sensitivity analysis is not included as a means of discussing the reliability of the data, the influence of the building form and its energy system, the diversity of occupants' behaviour and, finally, the unpredictability of end-of-life scenarios. The refining and strengthening of this knowledge require a transdisciplinary approach and the definition of a wider research framework.

5.2. Beyond LCA: enlarging the methodological framework

Life cycle thinking provides the theoretical basis for a global approach to environmental issues and promotes multi-criteria analysis through a series of indicators that account for the many transformations generated by a product throughout its life trajectory. However, despite the fact that this conceptual framework assumes that the ecological impact caused by human activities goes far beyond the issue of climate change, many of the LCAs of windows only assess carbon and energy footprints or focus only on these indicators even when others are calculated. Thus, the result is a truncated vision that does not prevent the risk of the transfer of ecological burdens.

Nevertheless, no LCA can claim to be exhaustive. Defining a scope necessarily leads to the exclusion of parts of the interactions between the object of study, its users and the biosphere. Assumptions have to be made in order to define boundary conditions, thus calling for knowledge which goes beyond a quantitative approach of environmental issues and raises a series of questions which cannot be answered through an LCA alone: Is the air tightness of a window guaranteed when fitted as part of a renovation project? Are users able to comply with the maintenance protocol established by the manufacturer? Is there a risk of a rebound effect if windows are replaced by more efficient products? What is the service life of frames and glazing when also considering the use of the building? To what extent does the design of a product affect its recyclability potential?

The answers to these kinds of questions can radically change the modelling of an LCA. Moreover a better understanding of the interaction between windows, the occupants of a building and the environment would refine thinking at the interpretation phase. Such an objective requires the development of a methodology based on research tools that are not solely quantitative. This is the path followed in some of the studies [14,16,29,83] which attach greater importance to the behaviour of the occupants of a building.

According to the limitations highlighted by this review, one way to further develop the environmental analysis of dynamic elements, such as windows, would be to broaden the methodological framework by integrating sociological considerations into the first step of an LCA, i.e. in the definition of the goal and scope of the assessment. Through a practice-oriented literature review focused on the function of the studied product, a bridge would be built between LCA and the sociology of techniques, energy and the environment [84]. This would improve the definition of the scenarios investigated, strengthen the assumptions and broaden the understanding of uncertainties. Finally, the last step of an LCA, i.e. the interpretation phase, would discuss the results not only in terms of technical and industry issues, but also in relation to lifestyles and practices that determine the use and consumption of these products.

5.3. Linking windows design and environmental practices

This review has raised an additional major issue: a pressing need for research related to the management of the end-of-life phase of windows that are currently generally sent to landfill (section 4.3). While energy renovation policies are being encouraged in Europe and have led to the scrapping of many windows, we still need to maintain a broad investigative approach that combines environmental analysis and research by design.

We still need a better understanding of the current economic and technical issues that restrict the recycling and reuse of frames and glazing, as well as an analysis of how their design influences disassembly and repair practices (since assembly techniques greatly determine the trajectory of windows during and after their service life) [68,85]. As Carlisle and Friedlander [13] have pointed out, “further research is needed on how design and construction decisions affect collection and recovery rates in practice".

Questioning the design of windows can also broaden our understanding of this element and the way it conditions our relationship to the environment within a building. For instance, it has been shown that people's capacity to control the opening and closing of a window and/or its solar protection are essential factors in their perception of the atmosphere of a room, resulting in increased tolerance to more diverse climatic conditions [14,83,86]. The comfort zone is thus extended and can lead to a reduction in energy consumption. This opens up a large horizon that as yet remains unexplored. Through a comparative LCA of glazed elements which includes dynamic thermal simulations, different configurations could be assessed which would integrate considerations of different elements, such as opening systems, solar shadings, thermal curtains and/or more sophisticated devices that enhance interaction with the external environment. On a larger scale, such an approach would be able to provide guidance on architectural design strategies by defining or strengthening certain principles for sustainable construction, and by definition including considerations on practices of buildings.

6. Conclusions

The holistic perspective adopted in this article has made it possible to bring together a wide range of studies which analyse environmental issues related to windows, glazing and frames through a variety of methods. These studies followed quantitative and qualitative approaches which are highly complementary because of the diversity of knowledge they provide about diverse building elements, seen not only as technical but also as socio-ecological objects. Thus, the review of these studies has brought to light four important points which highlight the contributions of the research already carried out, as well as the questions that remain to be answered.

Firstly, it is clear that improving thermal performance of windows increases their ecological impact from cradle-to-gate, although there is no evidence currently available on how much the associated reduction in heating, cooling, and electricity loads offsets the environmental footprint of the production phase. There is indeed a prevailing uncertainty on the efficiency of high-performance windows, even though there is a consensus on the usefulness of double compared to single glazing, possibly in combination with some kind of solar control or low-emissivity coating.

Secondly, this remaining uncertainty appears to be the consequence of two methodological issues that have not yet been resolved convincingly in the studies reviewed. The first issue concerns the definition of the functional unit which varies between each study and makes it problematic to compare findings inasmuch as the windows may not assume the same functions or performance criteria. The second issue is directly related to this fundamental definition of the functional unit and concerns the modelling of the use phase which needs to take into consideration the indirect impact of glazing and frames on the energy consumption of a building. Thus, despite the diversity of the authors' responses to this issue, no research has integrated the multiple functions performed by a window (e.g. insulation, ventilation and lighting) into an environmental and dynamic analysis.

Thirdly, this review reveals the lack of knowledge relating to the end-of-life of windows, which are currently mostly sent to landfill. Accordingly, we need a better understanding of the current economic and technical issues that restrict the recycling and reuse of frames and glazing, as well as an analysis of how their design influences disassembly and repair practices since assembly techniques greatly determine the trajectory of windows during and after their service life. Such a subject is as much a matter of industrial ecology as it is of architectural and technical design, and, therefore, should lead to new resource management strategies as well as to new window assembly principles in order to foster repair, reuse and recycling practices.

Finally, with regard to these conclusions, it is clear that further research is needed to holistically assess the environmental footprint of windows according to the performance they seek to achieve, and to do so by integrating the multiple functions that this element performs. In order to achieve this, the methodological framework prevailing in the reviewed LCAs must be extended. This article defines numerous paths towards the development of such an appropriate framework which needs to take into account the socio-economic aspects related to the use of a window. Such a framework will need to include considerations related to the sociology of techniques and energy, which would provide a better understanding of the functions and uses of a dynamic element such as a window. Lastly, in order to claim to offer generalisable findings, more transparency on uncertainties as well as more sensitivity analyses around key issues are required, particularly regarding, the influence of the building form and its energy system, the diversity of occupants’ behaviour and, finally, the unpredictability of end-of-life scenarios.

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Appendix 1. List of the thirteen publications which are excluded, together with the reasons for their rejection

#	Studies	Reason for rejection
1	Novak 1994 [87]	Published before 2000, in German language
2	TU Wien 1997 [88]	Published before 2000, in German language
3	Kreiβig et al. 1998 [89]	Published before 2000, in German language
4	Weir 1998 [90]	Published before 2000
5	Weir and Muneer 1998 [28]	Published before 2000
6	Windsperger and Steinlechner 2000 [91]	Published in 2000, in German language
7	Chevalier et al. 2002 [15]	Unfinished
8	GEPVP 2005 [92]	No clear evidence of authors' independence
9	TNO 2007 [93]	Only energy consumption during the use phase is taken into account
10	Jaber and Ajib 2011 [94]	Only energy consumption during the use phase is taken into account
11	Grynning et al. 2013 [95]	Only energy consumption during the use phase is taken into account
12	Invidiata and Ghisi 2016 [26]	Concerns buildings located in Brazil
13	Carlos 2017 [96]	Only energy consumption during the use phase is taken into account

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