Fifth International Conference on Sustainable Construction Materials and Technologies. http://www.claisse.info/Proceedings.htm

ANTIFRAGILE WINDOWS:
HOW TO IMPROVE THE SUSTAINABILITY OF THE BUILDING SECTOR THROUGH THE DESCRIPTION OF THE TECHNICAL ELEMENTS

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ABSTRACT

To increase the level of sustainability of the built environment, it is necessary to understand that the life cycle of buildings and of the parts which make them up is articulated and complex. This complexity depends on the number of inputs and outputs of each process in the extraction of raw materials, production, installation, use, maintenance and end of life. Another type of non-negligible issues is linked to the method of analysis of the life cycle described, to the methods of data collection, to the processing and to the communication of information.
This paper analyses all of the above, starting from the description of the window system, which is made up of many different parts and materials and which is the subject of recent European regulations.
From the analysis of the market trends of windows and doors and from the reading of the certifications which attest to the sustainability of the life cycle of a window, it is possible to understand the complexity of the building system. This also makes it possible to identify critical issues and possible solutions for improving the efficiency of the set of rules, incentives and practices used to improve the level of sustainability of windows and, more generally, of buildings. The hope is that any innovation (in the field of needs, standards and technology) can lead to an improvement in the sustainability of construction products. The goal is to make not only the windows "antifragile", but also all the other parts of the building system.

Keywords: Windows, Circular Economy, LCA, Sustainability, Recycle

IMPROVE THE SUSTAINABILITY OF THE BUILDING SECTOR

When we talk about sustainability, it is necessary to consider many heterogeneous and closely-related aspects. This is the reason why it is difficult to describe the sustainability of a building, of a technological system, of a technical element and of a material used in construction.

Each building is designed to respond to specific needs. Each need meets one or more requirements (a requirement is a required quality as well as a specific and measurable question). The correspondence between a requirement (a specific question) and a performance (an answer) guarantees the attainment of a certain level of quality (the quality levels vary depending on how good an answer is given). Similarly, the environmental quality of a building can be assessed by using the indicators used for construction products and by adding organisational and systemic assessments. These assessments are important because they refer to invisible processes, which contribute to the coordination of the knowledge and skills of those who work for and in the construction process.

We must also consider that a high-performing building is not necessarily sustainable. Designing a building with reduced (or zero) energy consumption is one of the challenges with which designers are increasingly confronted. But planning for sustainability also means considering, in addition to the energetic aspects, the behaviour of the building and of its parts throughout the life cycle. And the life cycle is longer than the time for which the building is used and during which energy is consumed for its operation.

The description of the building in its physical and immaterial parts and the analysis of these in an analytical way is the starting point for reading and planning the relationship between the construction, its collateral activity and the natural environment. Each building is not just a set of constructive elements, but it is a complex system, a combination of different functions having spatial distribution, morphological articulation and micro-environmental characteristics.

The detailed analysis of the environmental compatibility of each technical element provides useful information to understand the complexity of the building. This analysis allows us to pursue the objective of preserving the value of products and materials by eliminating (as much as possible) wasteBeing aware of the scarcity of natural resources leads us to conceive of waste as resources and not as waste: the idea of "waste pollution" (which promotes incineration or landfill) is abandoned and waste is reintroduced into production cycles (Longo, 2007) so that the quality and value of the reused materials does not diminish.

This type of studies and reflections has caused the evolution of definitions and of LCA (Life Cycle Assessment) procedures. The first theorisations date back to the 70s and the first ISO standards since 1997. The standards currently in force date from 2006 and propose a "*from Cradle to Cradle*" approach, which emphasises the end-of-life phases of the product and re-introduces what are defined as Secondary Raw Materials, and no longer as waste, into the production cycle (EC, 2008/98/EC). In this scenario, the windows and doors sector is very interesting for two reasons:

- the tax reductions for the energy requalification of buildings encourage the replacement of existing windows and doors, and this substitution activity produces a quantity of waste;
- technological innovation is making many of the frames which have been installed in the last decades obsolete, which makes us reflect on the life cycle of the windows and doors and on the destiny of abandoned products.

ECODESIGN IN THE FIELD OF WINDOWS AND DOORS

The European Union Directive 2005/32/EC-EuP (with binding effectiveness) and 2009/125/EC-ErP (which extends its contents), define *ecodesign* as "the integration of environmental aspects into product design with the aim of improving its environmental performance throughout its whole life cycle". This definition highlights two significant themes: the environmental impact of the product, i.e. "any change to the environment deriving in whole or in part from products during their life cycle" and the life cycle, i.e. the set of "consecutive and connected stages of a product from its use as a raw material to the final disposal". The rules which apply these Framework Directives encourage the adoption of common procedures to inform buyers about the environmental characteristics of the products.

The environmental characteristics which are communicated describe the correct and sustainable use of the products and/or define the so-called "ecological profile" of the products, which lists the advantages linked to eco-design. These communications take into account the entire life cycle of the product and all of its most significant environmental aspects, including energy efficiency.

Among the founding criteria of eco-design are the selection and use of raw materials, manufacturing, transport and distribution, installation and maintenance, use and end-of-life phases (which define the methods of disposal or recycling of the components). Each stage of the life cycle must be described through consumption (of materials, energy and other resources), emissions (in air, water and soil), pollution, generation of waste and possibilities for the re-employment or recycling of materials.

Products which can be EC certified only after the fulfilment of these commitments are becoming increasingly numerous. The 2005 Directive was addressed only to energy-using products (EuP) and the most recent Directive of 2009 is dedicated to components which do not require energy to operate but which, in their use phase, influence the energy consumption of the building (Energy-related Products, ErP). Windows and doors are regulated by the Directive of 2009 because they are components of the building envelope which have a significant impact on the energy consumption of a building. This incidence can reach 30-40% of total consumption, which is a variable value depending on the construction technology of the frame and of the reference building (Capolla, 2011).

Window and door design has a high potential in terms of energy saving and the European Commission has underlined the need to define a common

environmental impact assessment model for windows and doors: this assessment must be carried out in compliance with the LCA procedures defined by the ISO 14040: 2006 standard (Van Elburg, 2015).
For a correct LCA evaluation it is essential to correctly define the functional unit, that is the unit of measurement on the basis of which to calculate the various environmental impacts. In the windows and doors sector, the choice of functional unit is complicated because the dimensions, shapes and types of windows and doors available on the market are very different from one another.
The life cycle of a window frame, to be analysed in full, must consider the phases of production, use and end of life. This must be done in relation to a scheme consisting of three modules:

- upstream module, which includes the extraction and/or production phases of the raw materials and of the sub-components of the finished product;
- core module, which contains the main activities and outputs related to the production of the component itself;
- downstream module, which contains the activities related to the installation, use, maintenance and end of life of the product.

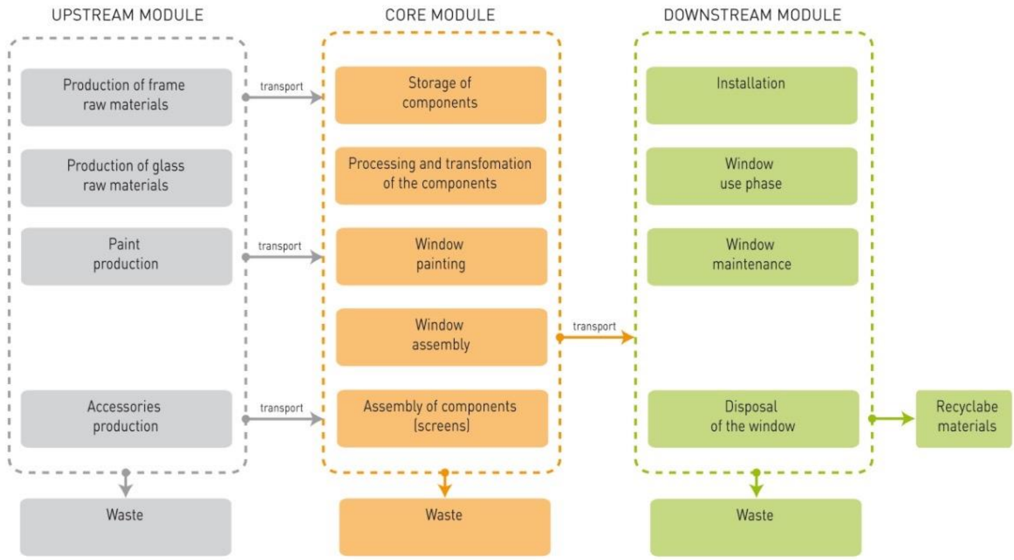


Fig.1 Flow chart of the life cycle of a window frame.

Despite the complex assessment, the LCA analysis is increasingly used for the description of windows and doors sold in Europe (Baldo et al., 2008). Some manufacturers have certified their products using EPD (Environmental Product Declaration) which are Type III environmental declarations (ISO 14025:2006). These certifications provide quantitative data on the environmental profiles of products which are calculated using the LCA method described in the ISO 14020 series of standards, which establish guidelines and principles for the development of voluntary environmental declarations.

	Product Type	Producer	Date	Ente	Funcional Unit	PCR	UPSTREAM	CORE		DOWNSTREAM													
							Raw Materials	Transport	Manufacturing	Transport	Installation	Use	Maintenance	Repair	Replacment	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Recycle
							A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
1	Window	Cormo	2008	EPD® Inter.	Window 120x140 mm	2011:23 Builders' joinery and carpentry of wood	x	x	x	x	x	x	x										
2	Frame	Fresia	2014	EPD® Inter.	1kg frame	2012:01 Construction products and construction services	x	x	x														x
3	Frame	Firat	2015	EPD® Inter.	1kg frame	2012:01 Construction products and construction services	x	x	x													x	
4	Glass film	Saint Gobain	2012	EPD® Inter.	1mq	2012:01 Construction products and construction services	x	x	x	x	x	x							x	x	x	x	x
5	Window	Velfac	2000 - 2006	EPD Danmark	Window 123x148 cm	-	x	x	x	x		x	x						x	x	x	x	x
6	Window	Shuco	2011	EAA	Window 314,5x210 cm	Aluminium Building Products	x	x	x	x	x	x	x						x	x	x	x	x
7	Window	Sapa Building Systems	2014	EAA	Window 165x230 cm	Aluminium Building Products	x	x	x	x	x	x	x						x	x	x	x	x
8	Window	TECHNAL	2007	EAA	Window 145x145 cm	Aluminium Building Products	x	x	x	x	x	x	x						x	x	x	x	x
9	Window	Jansen	2012	IFT	1m2 di finestra 123x148 cm	ift "Fenster" (Windows) PCR-FE-1.1 : 2010	x	x	x	x	x	x	x	x			x		x	x	x	x	x
10	Window	Forster	2013	IFT	1mq of window of 123x148 cm	ift "Fenster" (Windows) PCR-FE-1.1 : 2010	x	x	x	x	x	x	x	x			x		x	x	x	x	x
11	Window	Eduard Hueck GmbH	2011	IFT	1mq of window of 123x148 cm	ift "Fenster" (Windows) PCR-FE-1.1 : 2010	x	x	x	x	x	x	x	x			x		x	x	x	x	x
12	Window hardware	Insulbar	2013	IFT	1 kg	Semifinished products PCR-HZ-1.0:2013	x	x	x												x		x
13	Glass	Euroglas GmbH	2012	IFT	1mq glass of 1 mm	Flachglas im Bauwesen (Glass in Building): PCR-FG-1.1 : 2011	x	x	x										x			x	x
14	Window	Andersen Windows	2015	UL Envi.	1mq of window of 120x150 cm	Earthsure Cradle to Gate Window Product Category Rule 2015	x	x	x														
15	Window	Kawneer	2015	UL Envi.	1mq of window of 120x150 cm	Earthsure Cradle to Gate Window Product Category Rule 2015	x	x	x														
16	Window hardware	Sika	2014	IBU	1kg resiin	Reaction resin products, 07.2014	x	x	x	x	x												x
17	Window	QKE	2014	IBU	window 123x148 cm	Windows and doors, 10-2012	x	x	x	x	x	x			x				x	x	x	x	x
18	Window	QKE	2014	IBU	window 123x148 cm	Windows and doors, 10-2013	x	x	x	x	x	x			x				x	x	x	x	x
19	Window hardware	Fachverband Schloss- und Beschlagindustrie	2011	IBU	window 123x148 cm	Locks and Fittings: 2010-12	x	x	x														x
20	Frame	EGE PROFİL WINSA	2015	IBU	1kg frame	Windows and doors, 11-2014	x	x	x														
21	Window	NorDan AS	2014	EDP Norge	window 123x148 cm	NPCR014 rev.1 windows and doors	x	x	x	x			x							x		x	x
22	Window	Nordvestvinduet AS	2015	EDP Norge	window 123x148 cm	NPCR014 rev.1 windows and doors	x	x	x	x			x							x		x	x
23	Window	Norgesvinduet Kompetanse AS	2016	EDP Norge	window 123x148 cm	NPCR014 rev.1 windows and doors	x	x	x	x			x							x		x	x
24	Window	H-vinduet Magnor AS	2014	EDP Norge	window 123x148 cm	NPCR014 rev.1 windows and doors	x	x	x	x			x							x		x	
25	Window	Zuhaizk	2018	EPD® Inter.	window 123x148 cm	NPCR 014 rev1 Windows and doors (EPD Norge)	x	x	x														
26	Glass	Saint Gobain	2016	EPD® Inter.	1mq glass	2012:01 Construction products and construction services, version 2.01	x	x	x														
27	Glass	Saint Gobain	2016	EPD® Inter.	1mq glass	2012:01 Construction products and construction services, version 2.01	x	x	x														
28	Glass	Saint Gobain	2016	EPD® Inter.	1mq glass	2012:01 Construction products and construction services, version 2.01	x	x	x														
29	Glass	Saint Gobain	2017	EPD® Inter.	1mq glass	2012:01 Construction products and construction services, version 2.01	x	x	x														
30	Glass	Saint Gobain	2016	EPD® Inter.	1mq glass	2012:01 Construction products and construction services, version 2.01	x	x	x														

Fig.2 Collection of the EPDs related to the windows and doors sector identified by the authors in the period 2016-2017.

The environmental declarations of the frames which have been identified in the European context are not very numerous (30 EPDs have been identified at the end of 2018) and show a considerable variability in the analysis (the evaluation criteria differ a lot from each other). When measuring the impact of a window, the functional units and the process phases can be defined in a variable way. These can be interrupted just before or shortly after the use phase; often the end of life phase is excluded because, as stated in the EPDs made known, the recycling of the components is not the responsibility of the manufacturing company but of the professional who will take charge of the decommissioning of the window.

These are the reasons which, at present, exclude the end-of-life stage from evaluations. This phase, however, is significant in the overall environmental balance of the product. The importance of an adequate study of the end of life of a window can be understood by imagining the environmental impacts which can be avoided thanks to the recycling, recovery or reuse of materials. In LCA analyses, a building's operating period is generally set at 100 years. Instead, the useful life of a window is about 30-40 years, and this means that the impact of the production phase is relevant only in the first years of use of the building. By extending the phase of use of the windows over 30 years, the impact due to the operating phase significantly surpasses that relating to the manufacture of the product, mainly due to the progressive loss of performance of the window. The prolongation of the useful life of windows and doors shows how the use phase is highly significant for the purpose of calculating environmental impacts, and this should guide research towards the definition of impact assessment systems during the use phase (these studies may be more significant than those which analyse the overall impact of windows on the life cycle of buildings).

The "Sustainable Development and Equity" chapter of the "Climate Change 2014" (Fleurbaey et al., 2014) report explains the usefulness and convenience of LCA assessments and certifications communicated through labels, environmental statements or Carbon FootPrint (CFP) analysis. The latter, in particular, are indicated as an essential tool for improving the environmental efficiency of the products on the market (Fleurbaey et al., 2014). A CFP analyses calculates all the CO_2 emissions generated during the life of a product, from production to distribution to disposal or recycling at the end of its life. An adequate communication of these characteristics allows:

- consumers to choose by reading brands and labels which inform them about the environmental impacts related to the product;
- companies to work on reducing greenhouse gas emissions by identifying the most damaging production processes;
- the legislator to develop policies to offset the quotas of CO_2 emitted (carbon offset);

The use of labels, brands and other forms of certification has already managed to change the market trend. Consumer habits and producers' priorities have changed. Consumers who choose sustainable certified products allow companies to define new areas of the market in which ecodesign is an essential tool for product innovation. The adoption of brands and labels progressively leads to the reduction or elimination of the market of non-eco-compatible products. The sales curve moves towards more efficient products.

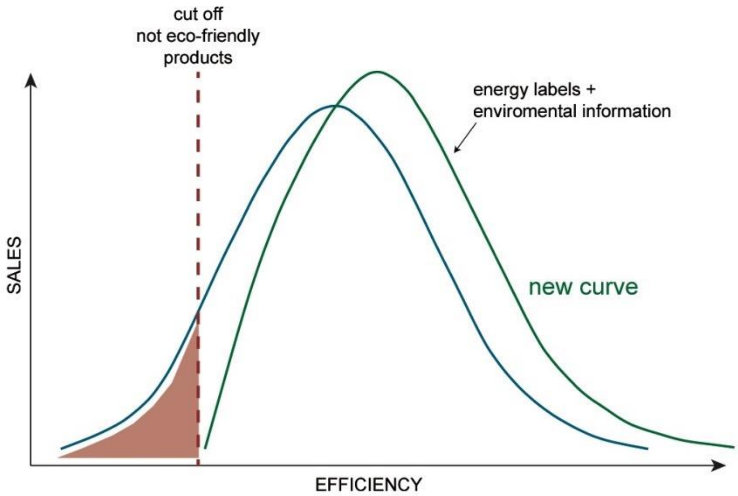


Fig.3 Graph which describes the impact of ecodesign in the purchase and sale of windows and doors.

DATA ANALYSIS

The analysis of several studies and environmental declarations dedicated to windows and doors shows that the use phase presents ever greater environmental impacts of the sum of the impacts developed in the other phases of their life cycle (GWP_{100} and Energy Consumption-CED). This consideration is valid by observing the matured data both in the short term (30 years) and in the long term (100 years) (Mosle, 2015). However, the studies analysed and compared to reach this consideration use different evaluation methods, especially for the analysis and evaluation of maintenance (in use) and recycling (at end of life).The maintenance phases are estimated in an average way, distributing a series of interventions - which can maintain the initial performance of the window frame unaltered - over the period of useful life. The data describing the end of life of windows and doors are not available; this phase of analysis is always addressed using the average data relating to the materials of which the window is composed. With regard to maintenance in the phase of use, estimates undervalue an important factor: currently, regulations and incentives favour the replacement of inefficient windows with new-generation products. Many of the replaced windows were installed between 1960 and 1980 and are replaced after an average use period of 30-40 years; there are rare cases of replacement after 100 years (time parameter used for LCA assessments of buildings). Moreover, the replacements are almost always preceded by restoration interventions which can also be of considerable importance (replacement of glass or entire parts of the frame, addition of double windows, etc.). Finally, the current regulatory provisions provide for the reduction of the transmittance of the frames in a way in which, over time, the value of thermal transmittance (U_w) is reduced more and more. In Italy, from 2006 to 2017, the U_w value was changed four times from 2.8 W/m^2K to 1.9 W/m^2K (for Italian climate zone E). This process has improved the quality of the internal environment of buildings, which perform better than before, and has favoured technological innovation, because it has led companies to produce increasingly efficient windows. In this perspective, the windows installed at the end of the 1990s or in the early 2000s, which have U_w transmittance of 2.0-2.2 W/m^{2}K, will be obsolete in a few years and will no longer perform. New replacement operations will be necessary for the implementation of products with U_w transmissions of 1.0-0.9 W/m^{2}K (which are already on the market today). This strategy of improving the window system will certainly result in the reduction of energy consumption of buildings in use, but will also imply the replacement or adaptation of windows which are only 15-20 years old.

Therefore, the LCA assessments of windows which consider 100 years of life cycle and few and minimal maintenance interventions (interventions based on statistical averages justified by the high durability of the materials) describe a scenario which is not plausible and which does not adhere to EU strategies. Therefore, a good LCA analysis must be based not only on past estimates and averages, but also on the prospects for the development of the construction sector. The Directives indicate that in future additional work will be carried out to reduce consumption by encouraging replacements and adjustments to windows with a 15-20 year period. All this greatly increases the weight of the maintenance phase and the end-of-life phase of the fixtures: phases which today are little analysed and for which there are few examples of recovery or full and traced recycling.

The quantities of profiles and products for recovered windows and doors are not known. The lack of data and good practices, combined with the progressive improvement strategies proposed by the EU, show that the window replacement activity will produce a huge amount of waste which, in the current state of affairs, cannot be estimated or managed correctly. This is in clear contrast with the objectives expressed by the EC Directives dedicated to ecodesign and ISO standards of the 14000 series: the replacement of the windows will lead to an increase in non-recyclable waste, the current production cycles of the frames are unable to use parts or materials which come from disposal operations and the disposal of the components of the window system will cause an increase in the environmental impact (because the end of life will be characterised by open cycle recycling activities after dismantling, energy recovery and landfilling; activities which weigh heavily in terms of LCA).

THE ADVANTAGES AND COMPLEXITY OF CERTIFICATIONS

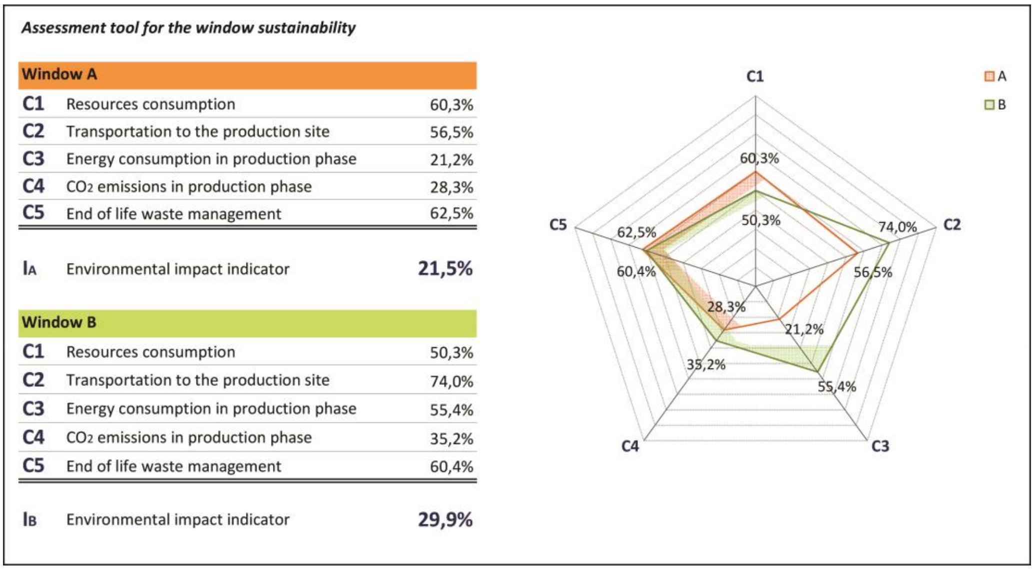
The increase in eco-efficiency in production is a prerequisite for the development of a sustainable society. Eco-design develops products of value and functionality equal or superior to those already available and characterised by a lower impact on the environment. The reduction of impact can be demonstrated by measuring the reduction in the amount of pollutants released into the atmosphere, into water, into the soil or by describing a more conscious use of resources in the phases of

production and the end of life of the product. This chain of relationships, to be able to bear witness to a real benefit for the environment, must be described with brands which refer to detailed studies.
This issue is not obvious: the many self-certifications make the environmental certification scenario variegated. The three types of certification described by the ISO 14000 series should not be in competition with each other: the different standards offer a wide range of opportunities for development and communication of information regarding the environmental compatibility of the products. What is missing is the familiarity of consumers with brands and certifications and the ability to understand that, behind some labels, there is a very complex and important study for the future progressive improvement of environmental quality. By imagining a progressive increase in the discretionary capacity of buyers of certified products and brand users, it is necessary to think of a parallel evolution of the tools for the definition of LCA analysis. At the community level, dissemination and awareness campaigns are being studied so that the theme of eco-design is not only the reserve of a few experts, but becomes public domain. At the moment, there is no common strategy to promote the concept of sustainability and efficiency not only among experts in the sector but also among consumers, companies and designers.
These considerations become urgent if we consider that the construction sector represents a strategic area for the development of certifications and the mitigation of impacts. The construction industry is responsible for 32% of global energy consumption, 19% of CO_2 emissions and 51% of electricity consumption (IPCC, 2014). Furthermore, the construction sector represents an important sector of economic development with over 1,300 billion euros invested in 2014 and with an annual growth trend of 2.5% in 2018 (Euroconstruct, 2018).

A SUSTAINABILITY ASSESSING TOOL FOR WINDOWS

To meet the need for more effective dissemination of environmental issues to consumers, the paper proposes a graphic method for the comparison between different windows to assess the sustainability of doors and windows based on existing LCA assessments. The use of a graphical user-friendily tool allows a greater diffusion of the evaluation method even among non-expert users.
Five criteria are detected to define a window sustainability classification. Since they use different measurement units, their value is expressed as a percentage. In this way they do not represent an absolute value but the incidence of the criterion on the total product impact. The selected criteria are:
1. Raw materials consumption: the criterion indicates the percentage by weight (kg) of virgin raw materials used in production. The amount of recycled material introduced into the production processes is therefore excluded and it is highlighted in an indirect way, as a complementary amount of the primary resources used.
2. Energy consumption during production and disposal: the criterion indicates the percentage of energy used in the production phase (“from cradle to gate”) and

in the disposal phase, compared to GER (Gross Energy Requirement) index. Energy consumption related to the use phase is excluded. Any values derived from waste energy recovery at end of life are included as positive contributions.
3. Carbon footprint of the production phase: the criterion indicates the carbon footprint related to the window production phase. It is expressed as a percentage of the overall GWP_{100} value.
4. Durability: the criterion indicates the time range, expressed as a percentage, that will elapse after the first replacement to reach the 100 years reference period.
5. Waste management: the criterion indicates the percentage of post-consume waste that is sent to landfill, compared to the total waste. The percentage of recycled or converted waste is so highlighted in an indirect way.
A general indicator of sustainability of the window frame (I) is identified by the average of the various criteria and is represented by the colored area in the graph. This highlighted area indicates the relative impact of the criteria adopted: a larger area indicates a product with high environmental impacts, a small area indicates a product designed according to the Eco-design guidelines. In addition, the overlap of different product graphics compares the results both in terms of overall impact, considering the colored area size, either in term of single criterion.


Assessment tool for the window sustainability

Window A		
C1	Resources consumption	60,3%
C2	Transportation to the production site	56,5%
C3	Energy consumption in production phase	21,2%
C4	CO_2 emissions in production phase	28,3%
C5	End of life waste management	62,5%
I_A	Environmental impact indicator	**21,5%**

Window B		
C1	Resources consumption	50,3%
C2	Transportation to the production site	74,0%
C3	Energy consumption in production phase	55,4%
C4	CO_2 emissions in production phase	35,2%
C5	End of life waste management	60,4%
I_B	Environmental impact indicator	**29,9%**

Fig.4 The proposed sustainability assessing tool for windows.

CONCLUSION

The proposed tool, accompanied by GWP100 and GER values, could be a useful assessing method of window sustainability. The methodology proposed in the paper has several advantages. First of all, it allows to compare different products analyzing specific aspects of their environmental impact. The general indices

(GWP100 and GER) provide a global assessment of impact while the use of the five criteria allows targeted analysis on specific phases or production processes. The radar graph can also be use as an user-friendly representation of window sustainability. In that way, the analysis results will be easier to communicate to the users and also to the producers, encouraging new researches to improve the most impactful aspects of the product.

The patterns of the circular economy can also appear complex in their description, as well as articulated in their development. But integrated product tracking systems and information models as the proposed one, which provide data and assessments during the life cycle of buildings, allow the mapping of raw materials along their route before, during and after their use in buildings.

The rupture of the traditional concept of the linear economy, characterised by supply-production-waste-use logics, allows us to wish the window system an antifragile future: "Antifragility is beyond resilience or robustness. The resilient resists shocks and stays the same; the antifragile gets better" (Taleb, 2014). According to Nassim Taleb, antifragility is a characteristic which distinguishes organic beings from inorganic beings, complex beings from simple ones. The window system is a complex system and, interpreted as a circular economy, acquires an animistic fascination in which, after any crisis (evolution of needs or legislation, replacement or maintenance), each part of the system can be stronger at the interior of a new product or building project, without accepting losses of material, quality or value. To turn this wish into an innovation, we have to choose products for window frames made of recycled or easily recyclable material (disassembled and decomposable), which is durable but at the same time easy to maintain and with low energy impact. Above all, a new project is needed for the products which make up the window system so that the constant increase in performance can also correspond to a reduction of the environmental impacts of the product during its entire life cycle.

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