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Interpreting environmental impacts of wooden windows based on existing EPDs: An application in Italy

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ABSTRACT

To meet climate targets, it is necessary to adopt robust and recognized methods, such as life cycle assessment (LCA), to evaluate emissions, particularly from building materials. As shown in the literature, embodied impacts have become as significant as operational impacts. The embodied impacts of a specific product are given in a transparent and quantitative manner in environmental product declarations (EPDs), based on LCA results. Windows play a crucial role in the energy performance of buildings. In fact, they typically account for 10–25 % of the exposed area of a building, resulting in more than 60 % of its total energy loss. In Italy, wooden windows make up 28 % of the window market and are the cheapest option for mild climates over a timeline of 60 years. However, an important element is still missing: a simplified interpretation of EPD results to enable straightforward, balanced comparisons of the environmental performance between alternatives. In this context, an analysis based EPDs of wooden windows is proposed, with a focus on production and use stages, for the six Italian climate zones. The three main steps of the study are: 1) evaluation of the influence of window properties on the embedded impacts; 2) assessment of maintenance scenarios; and 3) estimation of operational impacts regarding window properties and exposed climate. The results suggest that the influence of thermal transmittance, wood type and exposed climate is higher for cold climates due to better performing production materials and more frequent maintenance during service life.

1. Introduction

According to recent reports from the International Energy Agency [29], the floor area of buildings is expected to rise by 75 % between 2020 and 2050. In 2022, buildings accounted for 34 % of global energy demand and 37 % of energy and process-related carbon dioxide (CO_2) emissions [53].

To reduce operational energy demand, the construction sector has focused in the last years on improving the energy efficiency of buildings, introducing stricter requirements for energy-efficient buildings such as *Passivhaus* and nearly zero-energy buildings (nZEB) [16,33,48]. Some of these requirements are based on improving the building envelope by using products and materials with improved thermal performance to reduce the energy consumption for heating and cooling [3,15].

Windows are architectural elements that constitute 10–25 % of the building envelope area [47]. Due to their low thermal resistance in comparison to other elements in the building envelope, they are responsible for up to 60 % of the total energy loss in buildings [33,47].

Over time, innovative solutions have been developed to optimise the thermal performance of windows, such as multi-layered and vacuum glazing, selective and low-emissivity coatings, electrochromic windows and aerogels, among others [7,33,48]. Even though these developments and improvements have achieved a reduction in the operational energy consumption of buildings, they have also generated higher embedded emissions, i.e. emissions related to the production, transport, and End-of-Life (EoL)[16,28,34,48]. and therefore play a key role in the environmental impact of buildings [6].

A way to reduce embodied carbon is to replace raw material carbon-intensive raw materials used in construction with wood [54].

Wood remains the oldest material used for windows, and it has been widely used for aesthetic purposes, despite the availability and use of other materials [2].

However, wood is a hygroscopic material and therefore highly affected by moisture, requiring particular care in its use and processing. Furthermore, understanding its performance and potentially ensuring long-term protection and maintenance are crucial when it is used as a building material [25].

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Nomenclature

AP	Acidification Potential
ADP-e	Abiotic Depletion Potential for Non-Fossil Resources
ADP-f	Abiotic Depletion Potential for Fossil Fuels
EoL	End-of-life
EP-fw	Eutrophication Potential in Freshwater
EPD	Environmental Product Declarations
GWP	Global Warming Potential
LCA	Life Cycle Assessment
ODP	Ozone Depletion Potential
PCR	Product Category Rules
POCP	Photochemical Ozone Creation Potential
PVC	Polyvinyl chloride
U_w-value	Thermal transmittance of the whole window
WLC	Whole Life Carbon

According to the study by Tarantini et al. [50] and as indicated in Fig. 1, window production is the life stage with the highest impact on all three impact categories considered (80 % in GWP, 62 % in AP and 56 % in POCP), followed by the use stage (about 20 % in GWP and POCP and 40 % in AP), while the contribution from the maintenance stage is low except for POCP (18 %).

This is reflected in the Whole Life Carbon (WLC) approach indicated in the recast Energy Performance of Buildings Directive (EPBD), which highlights that making good choices about efficient building practices and materials can have a huge impact on both operational and embodied carbon emissions [10].

To achieve more comprehensive results, the recast EPBD has, with support by several initiatives, recently incorporated whole-life carbon assessments into building performance evaluation.

Whole-life carbon encompasses both embodied carbon (from materials and construction) and operational carbon (from energy used during the building's use), resulting in the total greenhouse gas emissions and their related impact on climate change throughout the entire lifespan of a building.

Across the EU, several national initiatives have aimed to establish methodological, data, and reporting frameworks for entire life cycle performance [57].

An appropriate method to support the WLC evaluation is the Life Cycle Assessment (LCA). LCA has been introduced as a mandatory calculation method for new buildings in some European countries, and it is expected to be adopted in all member states by 2030. In fact, the LCA method is commonly used to calculate GHG emission reduction potentials, whether at the material, building, or building stock level [4]. One of the ways to perform a building LCA is to gather the environmental impacts on the product by analysing Environmental Product Declarations (EPDs) from producers [58].

EPD data from manufacturers, rather than generic secondary data from databases, can significantly reduce the uncertainties in the LCA results.

Loli et al. [35] demonstrated a 15 % difference in GHG emissions and impacts in LCAs conducted for the product stage (modules A1-A3 of EN 15804).

In Italy, the LCA, and in particular EPDs, are required by the Green Public Procurement regulations as part of the requirements related to building materials.

The International Reference Life-Cycle Data (ILCD) System, a European framework to develop consistent and robust life-cycle data and studies, recommends using specific data in LCA, such as EPD [56]. Product-specific data in the form of EPDs is also advocated by various Green Building Rating Systems and sustainability frameworks, such as DGNB and Level(s). This is also reflected in literature, which demonstrates that by comparing the influence of generic and specific datasets on LCA results, EPDs offer a significant advantage when used as a data source [17].

EPDs are voluntary labels to provide in a reliable, accurate and verified manner, especially in business-to-business (B2B) communication, transparent and quantitative environmental impact results from a specific product based on LCA results [8,9,18,22,40]. This type of label, also called a type III environmental declaration, is a third-party verified document that is regulated by the ISO 14025 standard. Once certified, a type III environmental declaration is registered and published by a Program Operator (PO), such as the International EPD® System, which besides the registration also manages the publication of the instructions to develop the label and product category rules.

In particular for construction products, EPDs must comply with specific rules, requirements, and guidelines called Product Category Rules (PCR) that are based on EN 15804. The PCRs for Windows and doors was provided by EN 17213, which expired in 2020 and is currently under revision [14].

EPDs are primarily used to compare and communicate LCA results and do not provide information about the product's environmental superiority or inferiority [12]. Therefore, to assess how a design solution affects the environment, designers need to conduct a comparative assessment. This means referring to "the superiority or equivalence of one product versus a competing product that performs the same function" [30,32].

In the construction sector, comparing EPDs within the same product categories is inherently complex in practice. According to various studies [24,49], insufficient harmonisation and the unregulated development of PCRs are thought to contribute to this complexity,

These limitations prevent designers from drawing clear, objective conclusions about environmental performance in building design, leading to uncertainty and subjective decision-making.

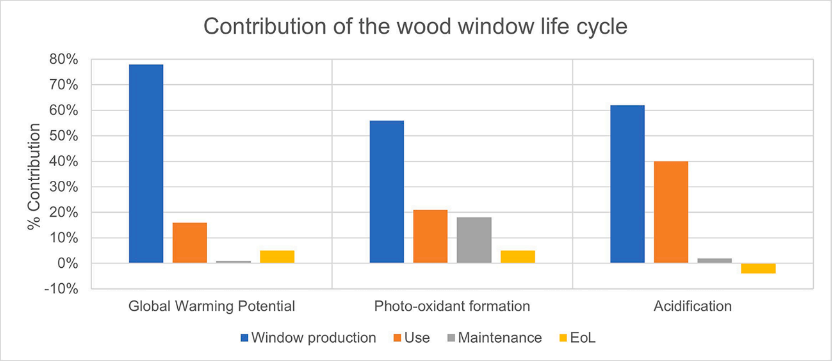

Fig. 1. Contribution of the wood window life cycle to Global Warming Potential [kg CO_2-eq.], Photo-oxidant formation [kg C_2H_4-eq.], and Acidification [kg SO_2-eq.].

In order to investigate this issue, a preliminary review of a number of EPDs related to windows published by the best-known European POs is conducted, identifying approximately 360 EPDs. Of these, polyvinyl chloride (PVC) and aluminum are more popular, followed by aluminum-clad timber, while wooden windows are the least monitored and analysed in the market, even if in Europe they account for a 24 % market share [23].

Furthermore, most EPDs analysed do not report further modules other than the product stage, even though the newest version of the EN 15804:2012 has expanded the minimum mandatory scope to incorporate the EoL stage [19]. Nowadays, similar studies exist for PVC, aluminum or aluminum-clad timber windows, but there is no specific analysis for wooden windows. This represents a limitation for architects, engineers, and LCA experts who intend to compare the environmental performance of wood-based windows based on their EPDs.

The selection of windows with the lowest life-cycle environmental impacts in an early-design stage is important to minimise the impacts of buildings. A streamlined LCA is still required for an integrated environmental and cost assessment of windows that fully incorporates embodied and operational energy assessments of windows at the early stages of building design, while also minimising cost and environmental performance [46].

Given this context, the study presents a holistic approach to rapidly guide the selection of an optimum wooden window system in order to reduce the environmental impacts of the building and to perform a more comprehensive LCA of windows.

A simplified LCA method has been applied to compare the impacts of alternative wooden windows using EPD data, considering the two main life cycle stages: production and maintenance.

Three main factors: window properties (U_w-value, wood and glazing types), and maintenance scenarios have been considered as input variables.

This approach can support window selection in a sustainable building design process, detailing product- and maintenance-related impacts, rather than focusing solely on the production phase.

In addition, this article investigates the consistency of the results provided by the EPDs published to date, given the more robust LCA datasource, in the most known European Program Operators.

This study encompasses a set of glazing and wood frame solutions that cover a wide range of thermal transmittance and outdoor exposure for windows. Hence, this approach can also be used to perform an environmental LCA of the other popular window solutions in the market with a wide range of materials, frames and values of thermal transmittance.

The first part of the paper is devoted to a review of the EPDs of wooden windows according to EN 15804 and determining the main characteristics that are further analysed in the study: thermal and acoustic insulation, optical properties, mechanical properties, and environmental impacts. The approach followed in the present research regarding measurements and evaluations are then reported. The results of various analyses of a wooden double-glazed window chosen as a reference sample and its alternative, optimised design are presented. Many different window configurations were considered in order to evaluate the influence on the various properties, and three comparative assessments were performed to consider the different environmental impacts. Finally, the discussion presents the overall performance, considering all the various aspects.

2. Background

2.1. Key enablers in defining environmental profile of window

Windows act as a connector between indoors and outdoors, supporting adequate air-conditioning by supplying thermal insulation and natural lighting, and protecting against bad weather or external factors (e.g. atmospheric pollution, insects) [5,45]. When selecting the type of window to install in a building, several aspects need to be considered: thermal transmittance, which is related to frame material and glazing type, cost, maintenance requirements, etc.

Different materials are used to produce the window frame: PVC, aluminum, wood, and aluminum-clad timber. In Italy, the volumes of sales for the window and door market reached €4.6 billion 2018, corresponding to 7.5 million window units and 8.8 million m^2. Based on Garzia [23], the Italian market is expected to continue expanding, reaching, the €5.3 billion and 8.4 million window units by 2022 despite the decreasing demand from 2020 due to the Covid-19. More specifically, in 2020, the Italian window market shares for PVC, aluminum, and wood materials in volume were 3.01 million units (43 %), 2.31 million units (33 %) and 1.68 million units (24 %), respectively, which in value represented €1.62 million (36.5 %), €1.55 million (36 %) and €1.26 million (28.5 %).

Two important aspects which significantly affect the environmental performance of the various types of window are durability and maintenance frequency during the service life, considering the climate exposition of the window. In this regard, Menzies et al. [38] have estimated that the Service Life Planning for windows based on ISO 15686–8 methodology is 56–65 years for timber and 71–83 years for aluminum-clad timber. However, the service interval is about 7 to 8 years for wooden windows and 20 to 30 years for aluminum-clad timber in non-extreme areas (non-coastal areas at low altitude and areas within 0.5 miles of the coast, respectively).

Moreover, the environmental impacts of a window are not restricted to the window itself, as it is also has an impact on the overall energy characteristics of a building. The operational environmental impacts of the building are related to the energy requirements for heating and cooling to satisfy the comfort of the building's users. Windows are usually upgraded to reduce thermal transmittance, decrease wind draft in winter and the heat of the sun in summer; increase natural daylight, and raise acoustic insulation to reduce noise [41]. Another benefit from the use of technologically improved windows is the added resale value for the buildings.

2.2. EPD as LCA data source impacts

Life Cycle Assessment (LCA) is an established method to quantify the environmental impacts of products throughout their complete life cycle [44], taking into consideration both embedded and operational impacts. In the construction industry, LCA is increasingly used to support the selection of building materials, products, and elements based on a life cycle perspective [15,50,51]. LCA is standardised by the international standards ISO 14040:2006 + A1:2020 and ISO 14044:2006 + A2:2020 [30,31].

To perform LCA, the International Reference Life-Cycle Data (ILCD) System recommends adopting specific data to carry out consistent and robust LCA studies. In this regard, a common internationally adopted source is EPDs. EPDs are regulated by ISO14025:2011 and ISO 21930:2017 at a general level, and by the EN 15804:2012 + A2:2020 for the product category of construction products and materials[17].

EPDs reveal information on potential environmental impacts, resource use and waste generation [12], providing producers with the opportunity to understand the environmental impacts of their products and, when integrated into a building LCA, the relevance of the overall environmental performance of a building [13]. Moreover, following the same argument, certain Green Building Rating Systems (GBRSs), e.g. the *Deutsche Gesellschaft für Nachhaltiges Bauen* (DGNB), and building sustainability frameworks, such as Level(s), encourage the use of EPDs in the environmental assessment of buildings [17,40].

In recent years, EPDs have become more adapted for the performance of LCA studies, especially in the construction sector, where there is a higher demand for the quantification of environmental performance [39,43]. Nonetheless, EPDs present some shortcomings when used as a data source to evaluate the environmental impacts of buildings. In particular, most EPDs do not provide information on the complete life cycle of the covered product. Mainly due to the lack of data for life cycle stages beyond the product stage and to the previous version of the EN 15804:2012 + A2:2020, where only the product stage was mandatory, the scope of most EPDs is cradle-to-gate or cradle-to-gate with options. As Božiček et al. [12] pointed out, the interpretation of the LCA results is missing in EPDs. This is a critical issue, since comparative analyses must be conducted to assess the environmental performance of products when using EPD in decision-making processes. The correct interpretation and use of EPD and LCA results are essential, while the availability of EPDs for certain products and local contexts is still limited.

The aim of this research is to create a model to measure the environmental impacts of the production and use stages of a wooden window even when the technical data is limited. On the one hand, the production stage is evaluated to determine which properties have the greater impact on the variation in the environmental impacts. On the other hand, the use stage is categorised between the different climate zones so that it is adaptable to other geographical areas.

3. Methodology

A simplified environmental LCA approach has been proposed to easily and accurately compare the impacts of alternative wooden windows, taking into account their thermal transmittance value and maintenance attributes. This approach was developed by using the set of indicators and information provided in the EPDs released by European program operators up to 2024. The evaluation was performed both in a Microsoft Excel spreadsheet and using the SimaPro© software.

This study explores the influence of characteristic parameters of wooden windows on environmental impacts in the product and maintenance stages, respectively. To estimate the environmental impacts of the selected wooden windows, the Italian climate zone classification was taken as a reference and, in particular, its legislative minimum threshold U_w values for windows, given the key role played by thermal transmittance of windows in achieving low or zero energy buildings. In addition, the Italian context offers the opportunity to test our analyses in a broader and heterogeneous perspective.

As shown in Fig. 2, the research was carried out in 3 phases: (1) preliminary work, which included the collection and selection of EPDs as well as the definition of scenarios; (2) definition of environmental impacts in the following life cycle stages: production (considering the parameters wood type, thermal transmittance, size, and manufacturer) and use stage (focus on maintenance measures and considering thermal transmittance, size, climate conditions, and service life) and (3) development of suggestions to support an informed and targeted choice in the design stage regarding aspects that have a greater influence on the life cycle environmental impacts of wooden windows.

The focus of the research is on 11 wooden window varieties. The selection of these typologies allows for a broad cross-section of wooden windows, with a variety of glazing units (double-glazed and triple-glazed), wood types (6 species), and a heat transfer coefficient (U_w) that is appropriate for Italian climate zones.

Italy has a long extension from North to South with a complex orography, resulting in several climate zones. The Italian territory is classified into six climate zones ranging from A, indicating areas with up to than 600 heating degree days and higher temperatures, to F, indicating areas with more than 3000 heating degree days and lower temperatures (Fig. 3). Table 2 reports the HDD and threshold U-values of windows in different climatic zones in Italy according to Italian requirements.

The meteorological and climatic conditions of the different regions have constituted an issue for urban design and studies, impacting human thermal comfort and the use of space in terms of energy consumption for heating, cooling, and ventilation [37]. In this regard, requirements regarding U_w-values for windows, including frame and glazing units, are defined for each Italian climate zone in Table 1, which shows the values up to 2020 and those from 2021 [26]. The latter values were used for this study.

With reference to the threshold values shown in Table 1, the evaluation focuses on the U_w-values from 0.78 W/m^2K to 1.40 W/m^2K, meeting the strictest thermal transmittance requirements.

3.1. Collection and evaluation of EPDs (Step 1)

This first phase involved the collection and selection of EPDs of wooden windows from several known European EPD databases, as reported in Table 2. To ensure that the specific criteria for window properties for Italy are met, the data to be collected are EPDs referring to Europe published on available EPD platforms.

Nine European EPD platforms were consulted and seven of them had EPDs for wooden windows. These EPDs represent less than 1 % of EPDs

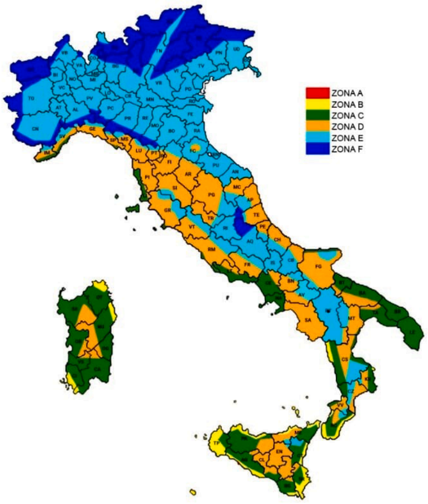

Fig. 3. Climate map of Italy. Italy is divided into six climate zones, which range from A (warmest), red, to F (coldest), blue.[11]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Methodology followed for the research.

Table 1
U_w threshold value for the Italian climate zones based on Italian legal requirements.

Italian climate zones	Heating Degree Days (HDD)	U_w threshold value [W/m^{2}K] DM 2015 (2015–2020)	DM 2015 (from 2021)
A	Up to 600 HDD	3.2	3.0
B	From 601 to 900 HDD		
C	From 901 to 1,400 HDD	2.4	2.0
D	From 1,401 to 2,100 HDD	2.1	1.8
E	From 2,101 to 3,000 HDD	1.9	1.4
F	More than 3,000 HDD	1.7	1.0

Table 2
List of the EPD platform included in this study.

EPD platform	Country	EPDs of windows	EPDs of wooden windows	Amount of EPDs collected
AENOR (*Asociación Española de Normalización y Certificación*)	Spain	2	0	0
CAPEM (Cycle Assessment Procedure for Eco-Impacts of Materials)	Belgium	3	3	3
EPD Italy	Italy	5	0	0
EPD-Norge	Norway	103	27	6
INIES (*Centre Scientifique et Technique du Bâtiment*—CSTB)	France	111	14	7
International EPD ® System	Sweden	91	12	2
IBU–EPD (Institut Bauen und Umwelt e. V.)	Germany	24	5	0
ITB (*Instytut Techniki Budowlanej*) EPD Program	Poland	10	3	3
Kiwa-Ecobility Experts (Kiwa-EE)	Germany	10	6	1

concerning construction products and 20 % of EPDs referring to windows. Approximately 40 % of EPDs from wooden windows come from the EPD-Norge platform (Table 2).

A total of 22 EPDs of wooden windows were selected in the surveyed databases. The products in the collected EPDs present different characteristics, such as glazing type, U_w-value and service life.

Furthermore, the products correspond to nine European companies and a French public-sector body (EPDs 17 and 18). In the EPDs, four types of wood were referenced: acetylated wood [1], pine, spruce, and oak. An overview of the EPDs found – including information on product manufacturer and commercial name, year of publication, program operator and PCR adopted – is shown in Table 3.

The collected EPDs were subsequently further analysed regarding window properties (U_w-value, type and geographical locations of wood, size, and glazing type) and EPD characteristics (validity, geographic representation). A summary is reported in Table 4.

Table 3
EPDs and criteria of exclusion from analysis.

EPDs	Criterion for exclusion
1-2-3	Wooden window frame without glazing
5-7-10	Fixed window
13	Misaligned values of LCI
17-18	Roof window
19-20-21	No information about the window’s components

The assessment started by classifying the attributes needed to assess and compare the performance of the windows in terms of environmental impact.

After collecting the EPDs and extracting the essential information, we proceeded to classify the EPDs based on the attributes necessary to assess and compare the environmental impact performance of windows.

This part of the analysis involved the definition of the functional unit, the system’s boundaries and then the exclusion of products not relevant to the study.

The functional unit definition is a crucial part of the first phase of the LCA (objective and scope).

According to the international LCA standard ISO 14040/44 [31,32], a Functional Unit (FU) is the “quantified performance of a product system for use as a reference unit” [19,30] and provides the basis for product comparisons.

However, defining the functional unit has been highlighted as a challenge in several studies. One of the challenges is the difficulty of adequately representing a product with multiple functions [21]. This is particularly true for windows, which, in addition to not being customised products (e.g. varying aesthetic and geometric characteristics), are made up of different elements, the variability of which in terms of raw materials and quantities is very large.

Based on the level of information gathered, the next phase involved compiling inventory for the three clusters of windows, which were grouped by threshold transmittance values following Italian climate zones and attributes (Table 5).

Table 6a and 6b present summaries of the most significant window parameters examined for zones F and E.

3.2. Environmental impact calculation EPD-based LCA at various life cycle stages (Step 2)

This stage aimed to analyse environmental indicators from the collected EPDs to meet the goals and scope of the analysis. Then, environmental LCA is performed using the LCA indicators from EPDs.

A more detailed assessment concerned the assumptions adopted in the EPDs, which are:

a. Declared or functional unit;
b. Life cycle stages assessed;
c. Service life of window.

The first aspect regarded the declared unit, which relates the material flows of a product to its environmental impacts and is applied when no functional unit can be applied-e.g. when the function of a product cannot be clearly described [19]. In this study, 1.00 m^2 was assumed as the functional unit and the environmental impacts were recalculated to refer to this unit value.

A second consideration was the life cycle stages, focusing on the product and use stages. However, some EPDs evaluating all the life cycle stages –i.e. cradle-to-grave– were also considered relevant as comparisons to cradle-to-gate or cradle-to-gate with options EPDs. In this case, two EPDs assess all the life cycle stages and twelve report at least one life cycle stage for each module. More than 75 % of the EPDs include module A4-transport to the construction site-in their scope, while five EPDs evaluate only the mandatory product stage (cradle-to-gate). The life cycle stages included in the collected EPDs are shown in Table 7.

The third assumption was related to the service life of the windows, which among the collected EPDs varies from 25 to 75 years. To determine the environmental impacts in the use stage, the average service life was 34 years. This was calculated after excluding seven of the twenty-one EPDs collected: EPDs 11 and 12 as they do not report service life; EPDs 17 and 18 since they refer to an average product made up of different windows rather than a specific product; and EPDs 1, 2 and 3 as they do not consider the glazing unit.

Thus, the following criteria were defined for the selection of the

Table 3a
Overview of Environmental Product Declarations collected.

N°	Producer	Product	Year	Country	EPD platform	Product Category Rules
1	Nederlandse Branchevereniging voor de Timmerindustrie (NBvT)	Fixed wooden window frame	2016	Netherlands	CAPEM	SBK-bepalingsmethode version 2.0, by SHR in 2016
2		Wooden window frame & turn part				
3		Wooden window frame & tilt and turn part				
4	Lian Trevarefabrikk AS	2-sided inward opening window	2015	Norway	EPD-Norge	NPCR014:2013 (version 1.0) windows and doors
5	Norgesvinduet Kompetanse AS	Fixed frame window	2016	Norway	EPD-Norge	NPCR014:2013 (version 1.0) windows and doors
6		Opening Window	2020	Norway	EPD-Norge	NPCR014:2019 (version 3.0) windows and doors
7	Nordvestvinduet AS	Fixed sash window	2015	Norway	EPD-Norge	NPCR014:2013 (version 1.0) windows and doors
8		Single window				
9		Top hung window				
10	Uldal AS	Fixed frame window	2018	Norway	INIES	NPCR014:2013 (version 1.0) windows and doors
11	Svenska Fönster AB	Wood window side-hung	2020	Sweden	International EPD® System	Construction products and construction services, 2012:01, UN CPC 54 (version 2.31)
12		Wood window fully reversible				
13	Arbor Fenex	Pine double-glazed window	2017	Turkey	INIES	N/A
14	DE-bois	Window or French window, double glazing	2018	France	INIES	NF EN 15804:2012 + A1:2014, NF EN 15804/CN:2016, and NF EN 16485:2014 [20]
15		Double-glazed window or French window	2020			
16		Triple-glazed window or French window	2020			
17	French Ministry	Double-glazed window with solid wood	2018	France	INIES	N/A
18		Triple-glazed window with solid wood	2019			
19	FAKRO	Wooden roof windows-double glazed	2018	Poland	ITB EPD Program	ITB-PCR A
20		Wooden roof windows-triple glazed				
21		Wooden roof windows-quadruple glazed				
22	SIA Arbo Windows	Outward-opening (Side swing- Fix and window)	2023	Latvia	Kiwa-Ecobility	EN 17213:2020

Table 4
Characteristic and technical information of the EPDs for wooden windows.

EPD ID	Declared unit [m^2]	U_w-value [W/m^2K]	Wood type	Service life [years]	Window area [m^2]	Glazing type
1	1.00	N/A	Accoya	75	4.33	Not considered
2	1.00	N/A	Accoya	75	2.16	Not considered
3	1.00	N/A	Accoya	75	2.52	Not considered
4	1.82	0.78	Laminated Pine	40	1.82	Triple-glazed
5	1.82	0.72	Laminated Pine	40	1.82	Triple-glazed
6	1.82	0.78	Pine	40	1.82	Triple-glazed
7	1.82	0.71	Pine	40	1.82	Triple-glazed
8	1.82	0.80	Pine	40	1.82	Triple-glazed
9	1.82	0.84	Pine	40	1.82	Triple-glazed
10	1.82	0.62	Pine	40	1.82	Triple-glazed
11	1.00	1.20	Pine and spruce	N/A	1.03	Triple-glazed
12	1.00	1.20	Pine and spruce	N/A	1.03	Triple-glazed
13	1.00	1.30	Pine	25	1.82	Double-glazed
14	1.00	1.40	Oak	30	1.33	Double-glazed
15	1.00	1.40	Tropical wood	30	1.00	Double-glazed
16	1.00	1.20	Tropical wood	30	1.00	Triple-glazed
17	1.00	1.40	Pine, oak, or tropical wood	25	1.00	Double-glazed
18	1.00	1.20	Pine, oak, or tropical wood	30	1.00	Triple-glazed
19	0.92	1.30	Pine	25	0.92	Double-glazed
20	0.92	0.97	Pine	25	0.92	Triple-glazed
21	0.92	0.58	Pine	25	0.92	Quadruple-glazed
22	1	1.20	Pine	30	1.00	Triple-glazed

EPDs:

- The EPDs must register a service life and consider the entire window in terms of a wooden frame and glazing unit. As reported before, seven EPDs were excluded (EPDs 1, 2, 3, 11, 12, 17, and 18).
- The EPDs must include at least one module of both the product (A1–A3) and the use (B1–B7) stages. Three of the remaining EPDs do not fulfil this requirement (EPDs 19, 20 and 21). The rest of the EPDs, 11 in total, were considered for further analysis.

Table 5
Overview of the analysed windows grouped by U_{w}-value.

Climatic Zone	U_{w}-value [W/m^{2}K]	EPD ID	Product	Wood type	Glazing type
F ≤ 1.00	0.78	**4**	2-sided inward opening window	Laminated Pine	Triple-glazed
	0.78	**6**	Opening Window	Laminated Pine	Triple-glazed
	0.80	**8**	Single window	Pine	Triple-glazed
	0.84	**9**	Top hung window	Pine	Triple-glazed
E ≤ 1.40	1.40	**14**	Window or French window, double glazing	Oak	Double-glazed
	1.40	**15**	Double-glazed window or French window	Tropical wood	Double-glazed
	1.20	**11**	Wood window side-hung	Pine and spruce	Triple-glazed
	1.20	**12**	Wood window fully reversible	Pine and spruce	Triple-glazed
	1.20	**16**	Triple-glazed window or French window	Tropical wood	Triple-glazed
	1.20	**22**	Outward-opening (Side swing- Fix and window)	Pine	Triple-glazed
	1.30	**13**	Pine double-glazed window	Pine	Double-glazed

- At least two types of wood for the window production and manufacturers in two geographical locations were required for the complete analysis. This condition is fulfilled through the heterogeneous set of EPDs, as they comprise four different wood types and six different European regions.
- A minimum of one EPD should consider all the modules of the use stage. This condition is satisfied in two cases: EPD 6 and EPD 13.
- The U_{w}-values of the windows are between 0.78 W/m^{2}K to 1.40 W/m^{2}K and are therefore in line with the defined requirements for the Italian climate zones (Section 3.1.1). Lower U_{w}-values imply a better quality of the window than those required for the Italian climate, which means that the optimal cost for the wooden window is not contemplated [26]. For this reason, EPDs 5, 7, and 10 are discarded on account of too low U_{w}-values.

After this classification, 11 EPDs were selected for further consideration in the study (Table 6a-b).

3.2.1. Product stage scenario

The first consideration concerned the exploration of impacts in the product stage, which includes:

- raw material supply (module A1), environmental impacts are produced as a consequence of the extraction of new materials and resources (primary materials) or the reuse of materials and resources (secondary materials);
- transport of the raw materials (module A2), the emissions generated through the transport from the extraction site to the production plant are considered;
- manufacturing stage (module A3) consists of the production processes, including the production of ancillary products and components, as well as assembly and transformation processes to obtain the final product [52].

Regarding the raw material supply, four different variables were evaluated to define their influence on the environmental impacts: wood selection, U_{w}-value, size, and manufacturer, which considers the aspects

Table 6a
Characteristics of wooden windows with a transmittance threshold value under that for zone F.

EPD ID	Window Type	Weight [kg]	Size [m^2]	U_{w}-value [W/m^{2}K]	Lifespan [years]	Wood Type	Weight [kg]	Glazing Type	Weight [kg]
4	2-sided inward opening window	64.43	1.82	0,78	40	Laminated Pine	19	3-layer glass	41.40
6	Opening window	65.00	1.82	0,78	40	Laminated Pine	16.57	3-layer glass	42.05
8	Single window	69.10	1.82	0,798	40	Pine	22.9	3-layer glass	41.04
9	Top hung window	67.78	1.82	0,841	40	Pine	22.9	3-layer glass	40.08

Table 6b
Characteristics of wooden windows with a transmittance threshold value under that for zone E.

EPD ID	Window Type	Weight [kg]	Size [m^2]	U_{w}-value [W/m^{2}K]	Lifespan [years]	Wood Type	Mass [kg/m^2]	Glazing Type	Mass [kg/m^2]
14	Opening Window	36.8	1.00	1.4	30	Oak	16.5	Double	16,9
15	Opening Window	30.7	1.00	1.4	30	Tropical	13.3	Double	15
11	Side-hung window	38.2	1.03	1.20	ND	51 % finger jointed and 49 % spruce	11.29	3-layer glass	22.29
12	Fully reversible window	40.1	1.03	1.20	ND	51 % pine and 49 % spruce	11.29	3-layer glass	22.29
16	Single window	42.6	1.00	1.20	30	Tropical wood (Africa, South America or South-East Asia	17.7	3-layer glass	22.5
22	Outward-opening (Side swing-Fix and window)	40.42	1.00	1.20	30	Pine	15	3-layer glass	20,31
13	2-sided inward opening window	25.15	1.82	1.30	25	Laminated Pine	9.18	2-layer glass	12.38

Table 7
Life cycle stages EN 15804:2012 + A2:2020 included in the EPDs assessed.

EPD ID	Life cycle stages Product stage			Construction process stage		Use stage							End-of-life stage				Benefits and loads beyond the system boundaries
	Raw material supply	Transport	Manufacturing	Transport	Construction – Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/ Demolition	Transport	Waste processing	Disposal	Reuse – Recovery – Recycling potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
1	X	X	X	X	X	X	X						X	X	X	X	X
2	X	X	X	X	X	X	X						X	X	X	X	X
3	X	X	X	X	X	X	X						X	X	X	X	X
4	X	X	X	X			X							X		X	X
5	X	X	X	X			X							X		X	X
6	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	X	X	X	X			X							X		X	X
8	X	X	X	X			X							X		X	X
9	X	X	X	X			X							X		X	X
10	X	X	X	X			X							X		X	X
11	X	X	X														
12	X	X	X														
13	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
14	X	X	X	X	X		X						X	X		X	
15	X	X	X	X	X		X						X	X	X	X	X
16	X	X	X	X	X		X						X	X	X	X	X
17	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
18	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
19	X	X	X														
20	X	X	X														
21	X	X	X														
22	X	X	X										X	X	X	X	X

Table 8
Overview of the 7 environmental impacts of 22 products identified by the assessment in the different life cycle stages (modules A1-D).

EPD	Life cycle stages		Global warming potential [kg CO2 eq.]	Ozone depletion potential [kg CFC-11 eq.]	Photochemical ozone formation potential [kg C2H4 eq.]	Acidification potential [kg SO2 eq.]	Eutrophication potential into freshwater [kg PO4- eq.]	Abiotic depletion potential for non-fossil resources [kg Sb- eq]	Abiotic depletion potential for fossil fuels [MJ]
1	A1 - A3	Product Stage	8,93E+00	2,93E-06	-1,15E-02	5,71E-02	2,03E-02	3,02E-05	
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage	2,89E+00	3,40E-07	3,95E-03	7,69E-03	1,38E-03	6,63E-06	
	C1 -C4	End of Life Stage	-2,95E+00	-1,34E-07	3,11E-03	-5,90E-04	-2,21E-04	2,65E-06	
	D	Benefits							
2	A1 - A3	Product Stage	2,37E+01	7,40E-06	-2,66E-02	1,74E-01	5,13E-02	2,01E-04	
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage	7,60E+00	9,24E-07	5,57E-03	2,03E-02	3,48E-03	3,21E-05	
	C1 -C4	End of Life Stage	-1,22E+01	-7,28E-07	1,86E-03	-1,00E-02	-2,31E-03	5,63E-06	
	D	Benefits							
3	A1 - A3	Product Stage	2,46E+01	5,93E-06	-1,60E-02	2,02E-01	4,21E-02	3,87E-04	
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage	6,00E+00	7,29E-07	4,75E-03	1,60E-02	2,74E-03	2,55E-05	
	C1 -C4	End of Life Stage	-8,10E+00	-4,73E-07	2,45E-03	-4,58E-03	-1,14E-03	4,79E-06	
	D	Benefits							
4	A1 - A3	Product Stage	8,62E+01	9,35E-06	4,51E-02	9,41E-01	8,86E-02	1,94E-03	1,55E+03
	A4 - A5	Construction Process Stage	1,63E+00	3,09E-07	2,85E-04	6,71E-03	1,10E-03	3,63E-06	2,56E+01
	B1 - B7	Use Stage	9,86E+00	1,19E-06	3,92E-03	4,75E-02	1,17E-02	4,34E-05	2,24E+02
	C1 -C4	End of Life Stage	4,02E+01	3,18E-07	6,77E-04	1,28E-02	2,52E-03	4,62E-06	2,88E+01
	D	Benefits	-2,10E+00	-2,78E-07	-9,05E-04	-9,87E-03	-2,31E-03	-3,60E-06	-2,84E+01
5	A1 - A3	Product Stage	9,44E+01	8,63E-06	4,16E-02	9,11E-01	8,25E-02	5,23E-04	1,31E+03
	A4 - A5	Construction Process Stage	1,50E+00	2,86E-07	2,63E-04	6,20E-03	1,02E-03	3,35E-06	2,50E+01
	B1 - B7	Use Stage	1,04E+01	1,09E-06	4,35E-03	5,24E-02	1,24E-02	4,90E-05	2,15E+02
	C1 -C4	End of Life Stage	2,57E+01	3,07E-07	9,18E-04	1,90E-02	4,11E-03	4,86E-06	3,01E+01
	D	Benefits	-1,10E+01	-5,77E-07	-5,26E-03	-9,35E-02	-6,26E-03	-7,46E-06	-1,11E+02
6	A1 - A3	Product Stage	1,01E+02	1,09E-05	4,68E-02	8,60E-01	9,99E-02	2,63E-03	1,44E+03
	A4 - A5	Construction Process Stage	6,49E+00	4,10E-07	3,36E-04	6,77E-03	1,14E-03	4,45E-06	3,48E+01
	B1 - B7	Use Stage	1,66E+02	1,31E-05	5,80E-02	1,02E+00	1,17E-01	2,75E-03	1,85E+03
	C1 -C4	End of Life Stage	3,96E+01	2,57E-07	5,57E-04	8,29E-03	1,90E-03	3,23E-06	1,10E+02
	D	Benefits	-2,74E+01	-1,33E-06	-1,28E-02	-1,40E-01	-1,48E-02	-2,82E-05	-2,87E+02
7	A1 - A3	Product Stage	8,12E+01	9,33E-06	4,17E-02	8,65E-01	8,64E-02	4,48E-04	1,37E+03
	A4 - A5	Construction Process Stage	1,61E+00	3,06E-07	2,82E-04	6,64E-03	1,09E-03	3,59E-06	2,53E+01
	B1 - B7	Use Stage	7,19E+00	6,88E-07	2,70E-03	3,18E-02	7,15E-03	3,01E-05	1,74E+02
	C1 -C4	End of Life Stage	3,22E+01	3,15E-07	9,58E-04	2,01E-02	4,39E-03	5,03E-06	3,02E+01
	D	Benefits	-8,13E+00	-4,95E-07	-3,84E-03	-6,60E-02	-5,08E-03	-6,42E-06	-1,00E+02
8	A1 - A3	Product Stage	8,37E+01	1,08E-05	5,05E-02	9,45E-01	1,08E-01	1,94E-03	1,62E+03
	A4 - A5	Construction Process Stage	1,74E+00	3,31E-07	3,04E-04	7,17E-03	1,18E-03	3,88E-06	2,74E+01
	B1 - B7	Use Stage	9,77E+00	1,16E-06	3,93E-03	4,73E-02	1,15E-02	4,28E-05	2,22E+02
	C1 -C4	End of Life Stage	4,83E+01	3,19E-07	1,00E-03	2,16E-02	4,80E-03	5,18E-06	3,06E+01
	D	Benefits	-1,11E+01	-7,10E-07	-5,48E-03	-8,42E-02	-7,04E-03	-8,81E-06	-1,40E+02
9	A1 - A3	Product Stage	7,92E+01	1,03E-05	4,92E-02	9,21E-01	1,04E-01	1,54E-03	1,56E+03
	A4 - A5	Construction Process Stage	1,72E+00	3,28E-07	3,02E-04	7,11E-03	1,17E-03	3,85E-06	2,71E+01
	B1 - B7	Use Stage	9,77E+00	1,16E-06	3,93E-03	4,73E-02	1,15E-02	4,28E-05	2,22E+02
	C1 -C4	End of Life Stage	4,82E+01	3,11E-07	9,80E-04	2,11E-02	4,71E-03	5,06E-06	2,99E+01
	D	Benefits	-1,09E+01	-7,08E-07	-5,41E-03	-8,29E-02	-6,99E-03	-8,79E-06	-1,38E+02
10	A1 - A3	Product Stage	1,00E+02	9,16E-06	3,97E-02	8,29E-01	8,29E-02	4,73E-04	1,47E+03
	A4 - A5	Construction Process Stage	2,11E+00	4,12E-07	3,38E-04	6,80E-03	1,14E-03	4,49E-06	3,50E+01
	B1 - B7	Use Stage	1,23E+01	1,06E-06	3,83E-03	5,84E-02	7,22E-03	3,76E-05	2,55E+02
	C1 -C4	End of Life Stage	3,76E+01	9,99E-07	1,25E-03	2,67E-02	5,31E-03	1,01E-05	1,58E+02
	D	Benefits	-1,30E+01	-5,18E-07	-4,67E-03	-7,10E-02	-6,53E-03	-8,83E-06	-1,28E+02
11	A1 - A3	Product Stage	7,76E+01	4,90E-06	8,00E-02	5,60E-01	1,00E-01	1,00E-02	3,39E+02
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage							
	C1 -C4	End of Life Stage							
	D	Benefits							
12	A1 - A3	Product Stage	9,44E+01	6,10E-06	1,00E-01	7,10E-01	1,20E-01	2,00E-02	3,39E+02
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage							
	C1 -C4	End of Life Stage							
	D	Benefits							
13	A1 - A3	Product Stage	3,18E+01	1,10E-05	8,29E-03	7,03E-02	1,73E-02	1,21E-03	5,67E+02
	A4 - A5	Construction Process Stage	1,21E+01	6,61E-06	1,81E-03	5,39E-02	1,38E-02	6,59E-05	1,26E+02
	B1 - B7	Use Stage	1,63E+01	1,19E-05	2,90E-03	9,90E-02	2,61E-02	9,86E-09	2,13E+02
	C1 -C4	End of Life Stage	1,42E+01	3,78E-08	3,47E-03	1,53E-03	4,58E-03	1,45E-08	3,64E+00
	D	Benefits							
14	A1 - A3	Product Stage	2,27E+01	2,60E-06	1,71E-02	3,20E-01	4,38E-02	3,35E-04	8,09E+02
	A4 - A5	Construction Process Stage	1,77E+01	1,18E-06	9,29E-04	3,38E-02	7,41E-03	3,12E-06	8,98E+01
	B1 - B7	Use Stage	3,17E+00	6,86E-08	4,97E-04	1,02E-02	2,83E-03	1,85E-05	3,85E+01
	C1 -C4	End of Life Stage	9,66E+00	1,34E-07	2,19E-03	3,10E-03	7,09E-04	1,11E-06	9,04E+00
	D	Benefits							
15	A1 - A3	Product Stage	3,39E+01	1,19E-05	2,17E-02	4,82E-01	6,57E-02	1,40E-03	8,73E+02
	A4 - A5	Construction Process Stage	1,46E+01	4,99E-07	3,53E-04	6,80E-03	1,15E-03	2,82E-06	2,73E+01
	B1 - B7	Use Stage	1,16E+00	1,06E-07	4,72E-04	5,11E-03	5,27E-04	3,46E-05	1,22E+01
	C1 -C4	End of Life Stage	1,61E+01	9,66E-08	9,78E-04	3,76E-03	8,83E-04	1,79E-06	7,48E+00
	D	Benefits	-6,38E+00	-5,83E-07	-1,33E-03	-1,55E-02	-1,23E-03	-2,85E-05	-8,81E+01
16	A1 - A3	Product Stage	5,17E+01	1,33E-05	2,89E-02	6,60E-01	8,51E-02	1,43E-03	1,16E+03
	A4 - A5	Construction Process Stage	1,50E+01	5,71E-07	4,03E-04	8,12E-03	1,39E-03	2,82E-06	3,32E+01
	B1 - B7	Use Stage	1,16E+00	1,06E-07	4,72E-04	5,11E-03	5,27E-04	3,46E-05	1,22E+01
	C1 -C4	End of Life Stage	2,10E+01	1,29E-07	1,30E-03	4,89E-03	1,14E-03	1,99E-06	1,00E+01
	D	Benefits	-7,48E+00	-7,40E-07	-1,03E-03	-1,61E-02	-1,56E-04	-1,80E-05	-1,08E+02
17	A1 - A3	Product Stage	7,48E+01	1,79E-05	4,41E-02	1,13E+00	1,68E-01	1,94E-03	1,59E+03
	A4 - A5	Construction Process Stage	2,77E+01	1,09E-05	2,89E-03	8,63E-02	2,21E-02	1,10E-04	2,03E+02
	B1 - B7	Use Stage	2,70E+01	2,00E-05	4,79E-03	1,65E-01	4,34E-02	3,91E-05	3,50E+02
	C1 -C4	End of Life Stage	2,60E+01	2,89E-07	5,34E-03	5,66E-03	7,53E-03	2,85E-06	1,76E+01
	D	Benefits							
18	A1 - A3	Product Stage	7,59E+01	6,29E-06	3,72E-02	7,93E-01	1,24E-01	1,04E-03	1,48E+03
	A4 - A5	Construction Process Stage	2,31E+01	1,56E-06	1,23E-03	4,47E-02	9,83E-03	4,07E-06	1,19E+02
	B1 - B7	Use Stage	4,68E+00	1,01E-07	7,29E-04	1,51E-02	4,17E-03	2,73E-05	5,68E+01
	C1 -C4	End of Life Stage	9,48E+00	2,20E-07	3,24E-03	5,11E-03	1,15E-03	1,82E-06	1,53E+01
	D	Benefits							
19	A1 - A3	Product Stage	6,13E+01	6,61E-05	8,78E-02	2,52E-01	4,28E-02	2,08E-04	4,22E+02
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage							
	C1 -C4	End of Life Stage							
	D	Benefits							
20	A1 - A3	Product Stage	6,40E+01	6,63E-05	9,20E-02	2,78E-01	4,56E-02	2,44E-04	4,42E+02
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage							
	C1 -C4	End of Life Stage							
	D	Benefits							
21	A1 - A3	Product Stage	6,67E+01	6,64E-05	9,61E-02	3,05E-01	4,83E-02	2,79E-04	4,63E+02
	A4 - A5	Construction Process Stage							
	B1 - B7	Use Stage							
	C1 -C4	End of Life Stage							
	D	Benefits							
22	A1 - A3	Product Stage	5,57E+01	8,69E-06	-	-	-	1,69E-03	9,67E+02
	A4 - A5	Construction Process Stage	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	B1 - B7	Use Stage	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	C1 -C4	End of Life Stage	2,92E+01	3,06E-07	-	-	-	2,87E-05	1,74E+01
	D	Benefits	-1,56E+01	-2,08E-06	-	-	-	2,03E-03	-2,24E+02

Table 9
The maintenance interval is based on coating and exposure with data retrieved from Vorwerk [55].

Initial coating	Exposure	Colour	Maintenance interval Regular inspection without using maintenance products [Years]	Yearly inspection and using maintenance products [Years]
Translucent	Protected weathering	Light	6	8
		Medium	7	12
		Dark	7	12
	Normal weathering	Light	3	5
		Medium	5	10
		Dark	5	10
	Heavy weathering	Light	2	3
		Medium	3	5
		Dark	3	5
Opaque	Protected weathering	Light	15	18
		Medium	12	15
		Dark	11	14
	Normal weathering	Light	12	15
		Medium	10	12
		Dark	9	11
	Heavy weathering	Light	7	10
		Medium	5	7
		Dark	4	6

Table 10
Cleaning process and the internal and external maintenance adopted for each EPD.

EPD ID	Cleaning	External maintenance Description	Cycles	Internal maintenance Description	Cycles
4	3 washes per year and a yearly consumption of 3 L of water and 1.50 dL of detergent for 1.82 m^2	Wood painted every 5 years	7	Wood painted every 20 years	1
6		Wood painted after 10 years and then every 6 years	5		
8		Wood painted every 8 years	4		
9					
13	No cleaning process	Wood painted every 5 years and includes the transport of the painter	4	Wood painted assumed every 20 years	1
14	Consumption of 360 L/m^2, but the detergent is not included	Wood painted every 10 years	2		
15					
16					

of technology and the local context.

Firstly, the impact of wood selection was analysed. The windows of the eight selected EPDs are made of three different wood types: pine, oak, and tropical wood. To determine if the wood type is relevant for the environmental performance, the impacts of the EPDs were compared. EPDs 14 and 15 were selected as they use different wood types (oak and tropical wood, respectively), while sharing the same U_w-value (1.40 W/m^{2}K) and manufacturer (DE-bois).

Secondly, the influence of the U_w-value was studied. The U_w-value is related to the thermal quality of the window-mainly the wooden frame and glazing unit. To detect its performance, EPDs 8 and 9 both from Nordvestvinduet AS but with a ΔU_w difference of 0.04 W/m^{2}K, and EPDs 16 and 15, form DE-bois with a ΔU_w difference of 0.20 W/m^{2}K were compared.

Thirdly, the influence of the manufacturer was compared between EPDs 4 and 6. They are built with the same wood type (pine), size (1.82 m^2), and U_w-value (0.78 W/m^{2}K), but by different manufacturers (Lian Trevarefabrikk AS and Norgesvinduet Kompetanse AS, respectively).

Finally, no assumptions to identify the performance of the raw material transport (distances, vehicle type, and other aspects, such as road condition) could be made, as the selected EPDs do not provide detailed information about transport scenarios. Also for the manufacturing stage, the judgement of experts consulted indicated that all the wooden window' manufacturers have similar processes as well as resource and energy consumption during the manufacturing process.

3.2.2. *Maintenance scenarios*

This section explored the principal aspects that affect window environmental performance regarding maintenance during the use stage These are: location and climate, wood treatment and maintenance of the wooden window and its frequency.

In relation to the influence of climate conditions on maintenance activities, the maintenance measures and frequency required to maintain the functional and thermal properties of the window were examined. Due to outdoor exposure of the wood to various weather conditions (humidity, precipitation, etc.), some physical and chemical changes in the properties of the wood can be caused by organisms: insects, which bite the wood tissue, or bacteria and fungi, which attack the wood increasing its permeability, reducing the moisture absorption, and decreasing the strength properties [36].

According to Herrera et al. [27], after being exposed to natural environmental conditions, thermally modified wood has a lower moisture content compared to non-thermally modified wood. However, both wood types experience a density decrease after exposure. Moreover, untreated wood has a faster degradation and shorter service life compared to treated wood.

Thirdly, maintenance of the wooden windows involves two main activities: cleaning and oiling of movable parts. The cleaning process should be regular (i.e. at least three times per year) and can be done in two different ways: with a lint-free cloth and a neutral detergent for dust, and, for heavy soiling, with a specific non solvent-based cleaning agent to avoid damaging the surface [42]. Furthermore, oiling all movable parts every six months with a suitable lubricating oil is necessary to ensure the function of all the fittings [55].

Finally, based on the direct experience of technicians representing the most qualified companies in the wooden windows sector, an overview of the maintenance scenarios for wooden windows is shown in

Table 11
Results of the seven indicators for the production of the four tested window models for Climate zone F. Orange and blue represent the minimum and maximum values for each of the 7 impact categories.

EPD	Functional Unit [m^2]	Lifespan [years]	U_w-value [W/m^{2}K]	GWP [kg CO$_2$–eq.]	ODP [kg CFC-11–eq.]	POCP [kg C$_2$H$_4$–eq.]	AP [kg SO$_2$ eq.]	EP-fw [kg PO$_4^{3-}$–eq.]	ADP-e [kg Sb–eq]	ADP-f [MJ]
4	1.00	34	0.78	4.74E + 01	5.14E-06	2.48E-02	5.17E-01	4.87E-02	1.07E-03	8.52E + 02
6	1.00	34	0.78	5.55E + 01	5.99E-06	2.57E-02	4.73E-01	5.49E-02	1.45E-03	7.91E + 02
8	1.00	34	0.80	4.60E + 01	5.93E-06	2.77E-02	5.19E-01	5.93E-02	1.07E-03	8.90E + 02
9	1.00	34	0.84	4.35E + 01	5.66E-06	2.70E-02	5.06E-01	5.71E-02	8.46E-04	8.57E + 02

Table 12
Comparison based on similar U_w–values within Climatic Zone F (unit: 1 m^2).

EPD ID	U_w–value [W/m^{2}K]	GWP [kg CO$_2$–eq.]	ODP [kg CFC–11–eq.]	POCP [kg C$_2$H$_4$–eq.]	AP [kg SO$_2$–eq.]	EP-fw [kg PO$_4^{3-}$–eq.]	ADP-e [kg Sb–eq.]	ADP-f [MJ]	AVERAGE
4 vs 6	0.78	17.1 %	16.6 %	3.8 %	8.6 %	11.7 %	35.6 %	−7.1 %	10.0 %
8 vs 9	0.80 vs 0.04	5.7 %	4.9 %	2.6 %	2.6 %	3.8 %	26.0 %	3.8 %	7,0%

Table 13
Comparison between EPDs with the minimum and maximum impacts in zone F (unit: 1 m^2).

EPD ID	GWP [kg CO$_2$–eq.]	ODP [kg CFC-11–eq.]	POCP [kg C$_2$H$_4$–eq.]	AP [kg SO$_2$–eq.]	EP-fw [kg PO$_4^{3-}$eq.]	ADP-e [kg Sb–eq]	ADP-f [MJ]
6 vs 9	27.5 %	5,8%	−4.9 %	−6.6 %	−3.9 %	70.78 %	−7,.7%

Table 14
Relative difference in the environmental indicators based on different offsets of U_w-value with same window size (unit: 1 m^2).

EPD ID	U_w-value [W/m^{2}K]	GWP [kg CO$_2$-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C$_2$H$_4$-eq.]	AP [kg SO$_2$-eq.]	EP-fw [kg PO$_4^{3-}$-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
4 vs 8	0.78 vs 0.80	3.0 %	−13.4 %	−10.7 %	−0.4 %	−18.0 %	0.0 %	−4.3 %
6 vs 8	0.78 vs 0.80	20.7 %	0.9 %	−7.3 %	−9.0 %	−7.5 %	35.6 %	−11.1 %
4 vs 9	0.78 vs 0.84	8.8 %	−9.2 %	−8.3 %	2.2 %	−14.8 %	26.0 %	−0.6 %
6 vs 9	0.78 vs 0.84	27.5 %	5.8 %	−4.9 %	−6.6 %	−3.9 %	70.8 %	−7.7 %

Table 15
Results of the seven indicators for the production of the four tested window models for Climate zone E. Orange and blue represent the minimum and maximum values for each of the 7 impact categories.

EPD	**Functional Unit [m^2]**	**U_w-value [W/m^{2}K]**	**GWP [kg CO$_2$–eq.]**	**ODP [kg CFC-11–eq.]**	**POCP [kg C$_2$H$_4$–eq.]**	**AP [kg SO$_2$–eq.]**	**EP-fw [kg PO$_4^{3-}$- eq.]**	**ADP-e [kg Sb- eq]**	**ADP-f [MJ]**
14	1.00	1.4	**2.27E + 01**	2.60E-06	1.71E-02	3.20E-01	4.38E-02	3.35E-04	8.09E + 02
15	1.00	1.4	3.39E + 01	1.19E-05	2.17E-02	4.82E-01	6.57E-02	1.40E-03	8.73E + 02
11	1.00	1.2	7.76E + 01	4.90E-06	8.00E-02	5.60E-01	1.00E-01	1.00E-02	3.39E + 02
12	1.00	1.2	9.44E + 01	6.10E-06	1.00E-01	7.10E-01	1.20E-01	2.00E-02	3.39E + 02
16	1.00	1.2	5.17E + 01	1.33E-05	2.89E-02	6.60E-01	8.51E-02	1.43E-03	1.16E + 03
22	1.00	1.2	5.57E + 01	8.69E-06	–	–	–	1.69E-03	9.67E + 02

Table 16
Influence of the wood selection: the relative difference in the environmental indicators of the product stage based on the same U_w-value and manufacturer (FU: 1 m^2).

EPD ID	U_w-value [W/m^{2}K]	GWP [kg CO$_2$-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C$_2$H$_4$-eq.]	AP [kg SO$_2$-eq.]	EP-fw [kg PO$_4^{3-}$-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
14 vs 15	1.40	–33.0 %	−78.2 %	−21.2 %	–33.6 %	–33.3 %	−76.1 %	−7.3 %

Table 17
Influence of the fittings selection: the relative difference in the environmental indicators of the product stage based on the same U_w-value and manufacturer (FU: 1 m^2).

EPD ID	U_w-value [W/m^{2}K]	GWP [kg CO$_2$-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C$_2$H$_4$-eq.]	AP [kg SO$_2$-eq.]	EP-fw [kg PO$_4^{3-}$-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
11 vs 12	1.20	21.6 %	24.5 %	25.0 %	26.8 %	20.0 %	100 %	0.2 %

Table 18
Influence of the U_w-value: The relative difference in the environmental indicators of the product stage is based on different offsets of U_w-value (FU: 1 m^2).

EPD ID	U_w-value [W/m^{2}K]	GWP [kg CO$_2$-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C$_2$H$_4$-eq.]	AP [kg SO$_2$-eq.]	EP-fw [kg PO$_4^{3-}$-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
16 vs 15	1.20 vs 1.40	52.5 %	11.8 %	33.2 %	36.9 %	29.5 %	2.1 %	32.9 %

Table 19
Average of environmental indicators per maintenance stage (FU: 1 m^2).

GWP [kg CO_2-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C_2H_4-eq.]	AP [kg SO_2-eq.]	EP [kg PO_4^{3-}-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
9.00E − 01	8.75E − 08	4.00E − 04	5.35E − 03	9.39E − 04	9.49E − 06	1.72E + 01

Table 9. The scenarios consider: the type of coating – translucent (varnish or stain) or opaque (painted) – the exposure, the colour (light, medium, and dark) and the maintenance interval with or without the use of maintenance products. The window exposure is classified into protected weathering (similar to a dry climate affected by humidity and temperature, but protected against rain and direct sunlight), normal weathering (between dry and cold climate), and heavy weathering (similar to a cold climate affected by extreme climatic conditions).

The maintenance scenarios adopted by available EPDs, namely cleaning frequency throughout the service life of the window and its external and internal maintenance, are summarised in Table 10. In EPDs 13, 14, 15, and 16, no specific criterion for internal maintenance of the wood is given, but for comparison purposes, a frequency of 20 years was assumed, as in the rest of the EPDs. Finally, based on the assumption expressed in the section 3.1, the environmental impacts were evaluated using the same dimensional unit as in the product stage and the number of maintenance cycles related to the service life was calculated.

4. Results

4.1. Environmental impacts during the production stage

4.1.1. Climatic zone F

The first evaluation concerns a comparative assessment in the production stage of window frames suitable for climate zone F. The adopted functional unit chosen is 1 m^2 of window area with a transmittance value below 1. The analysis covers 7 environmental indicators, the designation of which is presented in Table 2.

Table 11 presents the results of the environmental impact analysis carried out on windows with a thermal transmittance within the climate zone F threshold value (<1).

The first comparison is made within climate zone F between windows with the same transmittance (4 and 6), followed by 8 and 9 (Table 12). EPDs 4 and 6 have the same wood type, U_w-value, and size, but are produced by different manufacturers. In this case, the variation in the environmental impacts is relatively low (up to 26 %). An average difference of approximately 7 and 10 % is observed in the first and second cases, respectively (Table 11).

Secondly, we can observe that EPD 8 vs 9 (0.80 W/m^{2}K vs 0.84 W/m^{2}K), both of which are triple-glazed, have a relative offset in U_w-value of 4.8 %. The relative difference in the environmental impacts is low for most indicators, ranging from 2.6 to 5.7 % except for the ADP-e indicator.

In order to comprehend how each component influences the impacts, we then analyse the relationship between the main components of a window frame (double-glazing, timber, and fittings) and their relative weights. We identify which elements have the lowest and highest

Table 20
Environmental indicators of the use stage based on the window coating colour and climate zone (FU: 1 m^2).

Italian climate zones	Colour	Maintenance cycles	Impact indicators GWP [kg CO_2-eq.]	ODP [kg CFC-11-eq.]	POCP [kg C_2H_4-eq.]	AP [kg SO_2-eq.]	EP [kg PO_4^{3-}-eq.]	ADP-e [kg Sb-eq.]	ADP-f [MJ]
B	Light	3	2.70E + 00	2.63E − 07	1.20E − 03	1.60E − 02	2.82E − 03	2.85E − 05	5.17E + 01
	Medium	3	2.70E + 00	2.63E − 07	1.20E − 03	1.60E − 02	2.82E − 03	2.85E − 05	5.17E + 01
	Dark	4	3.60E + 00	3.50E − 07	1.60E − 03	2.14E − 02	3.76E − 03	3.79E − 05	6.89E + 01
D	Light	3	2.70E + 00	2.63E − 07	1.20E − 03	1.60E − 02	2.82E − 03	2.85E − 05	5.17E + 01
	Medium	4	3.60E + 00	3.50E − 07	1.60E − 03	2.14E − 02	3.76E − 03	3.79E − 05	6.89E + 01
	Dark	4	3.60E + 00	3.50E − 07	1.60E − 03	2.14E − 02	3.76E − 03	3.79E − 05	6.89E + 01
F	Light	5	4.50E + 00	4.38E − 07	2.00E − 03	2.67E − 02	4.70E − 03	4.74E − 05	8.61E + 01
	Medium	7	6.30E + 00	6.13E − 07	2.80E − 03	3.74E − 02	6.57E − 03	6.64E − 05	1.21E + 02
	Dark	9	8.10E + 00	7.88E − 07	3.60E − 03	4.81E − 02	8.45E − 03	8.54E − 05	1.55E + 02

Table 21
The relative difference in the environmental indicators of the use stage is based on different service lives for a wooden window (FU: 1 m^2).

Initial coating	Exposure	Colour	Maintenance interval without using maintenance products [Years]	Maintenance cycles over a service life of 34 years	Maintenance cycles over a service life of 60 years	Relative difference in impacts [%]
Opaque	Protected weathering	Light	15	3	7	233
		Medium	12	3	8	267
		Dark	11	4	8	200
	Normal weathering	Light	12	3	8	267
		Medium	10	4	9	225
		Dark	9	4	9	225
	Heavy weathering	Light	7	5	11	220
		Medium	5	7	15	214
		Dark	4	9	18	200

weights, both in terms of glass and timber, in relation to the total weight of the window, i.e. EPD 6 vs 9. The one with the highest weight in glass and fittings is 6 (65 % glazing unit and approx. 7 as fittings), and wood is EPD 9 (approx. 34 %) (Fig. 4).

We then concentrate on comparing the minimum (9) and maximum (6) values of the GWP indicator (Table 13). The comparison reveals that a higher proportion of glass and steel results in an increase in the GWP, ODP, and ADPe indicators, while a higher proportion of wood leads to an increase in the POCP, AP, EP, and ADP fossil values.

Consequently, the same window size (1.82 m^2) and different U_w-value offsets are analysed: $\Delta U_w = 0.02$ W/m^2K (EPDs 4 vs 8 and EPDs 6 vs 8) and $\Delta U_w = 0.06$ W/m^2K (EPDs 4 vs 9 and EPDs 6 vs 9) (Table 12).

In all these cases, the relative differences in the environmental indicators shown between those offsets are around 15 %, even if most properties are shared except the manufacturer.

These EPDs could also be analysed individually. For example, EPDs 6 vs 8 ($\Delta U_w = 0.02$ W/m^2K) and EPDs 6 vs 9 ($\Delta U_w = 0.06$ W/m^2K), with a different offset of U_w-value. In this situation, Table 14 shows that EPDs 6 vs 9 have some environmental impacts (GWP, ODP, and ADP-e) around 5 % higher than EPDs 6 vs 8, due to a higher offset of U_w-value. However, other environmental impacts (POCP, AP, EP-fw, and ADP-f) from EPDs 6 vs 8 are around 3 % lower compared to EPDs 6 vs 9.

4.1.2. Climatic zone E

In zone E, the preliminary comparison looks at frames with transmittance values of 1.40 W/m^2K (threshold value), weights of 36.8 and 30.7, and similar characteristics, with the exception of wood provenance (oak for EPD 14 and tropical wood for EPD) (Table 15).

For six out of the seven environmental indicators, a difference of 20–70 % is observed. One reason for this can be attributed to the origin of the wood, because a French manufacturer using oak from European forests requires shorter transport distances compared to tropical wood from Africa, South America, or South-East Asia (Table 16).

Another interesting aspect can be observed by comparing two fixtures where the weight of the fittings changes (EPD 11 vs 12). In this case, for approximately the same amount of double glazing and wood, the weight of fittings (>57 % steel and > 58 % aluminum) increases. The difference in the environmental impacts is about 20 % for most indicators, ranging from 20 to 26.8 % except for the ADP-e and fossil indicators (Table 17).

In addition, a comparison between windows with a relative offset of 14.3 % in U_w-value (1.20 W/m^2K vs 1.40 W/m^2K) − EPD 16 vs 15 − shows significant divergencies in the environmental indicators, giving differences in the environmental indicators from 2–52 % (Table 18).

However, it is difficult to establish a linear relationship between the U_w-value and the environmental impacts; in addition to increasing the weight of the glazing unit (by 50 % between double and triple glazing), the quantity of wood also increases (approx. + 33 %) (Fig. 5).

In agreement with the findings for Climate Zone F, the comparison indicates that an increased proportion of glass leads to higher values in the GWP, ODP, and ADPe indicators, while a higher proportion of wood primarily affects the POCP, AP, EP, and ADP fossils indicators.

Finally, the influence of the U_w-values over the environmental impacts GWP, ODP, POCP, AP, EP-fw, ADP-e, and ADP-f, are shown in Fig. 6 to Fig. 12, respectively. For the GWP, a trend seems to exist; the higher the U_w-value, the lower the GWP. However, this is not found with the 1.20 W/m^2K. For the ODP, ADP-e, and ADP-f two different trends appear, one between 0.78 W/m^2K and 0.84 W/m^2K and another between 1.20 W/m^2K and 1.40 W/m^2K, showing a correlation of the lower the U_w-value, the higher the environmental impacts. For the POCP, AP, and EP-fw no correlation exists, as the environmental impacts are more or less constant between 0.78 W/m^2K to 0.84 W/m^2K and the 1.40 W/m^2K, but are higher for 1.20 W/m^2K and lower for 1.30 W/m^2K.

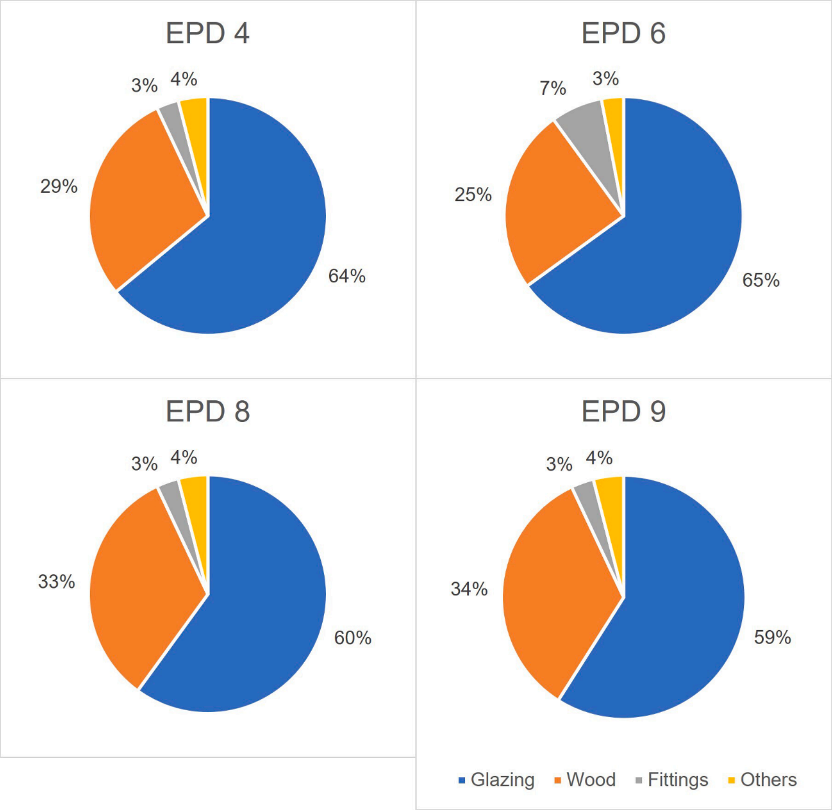

Fig. 4. Percentage contribution by weight of the three main window components compared to the total window weight (Climatic zone F, U_w-value ≤ 1.0).

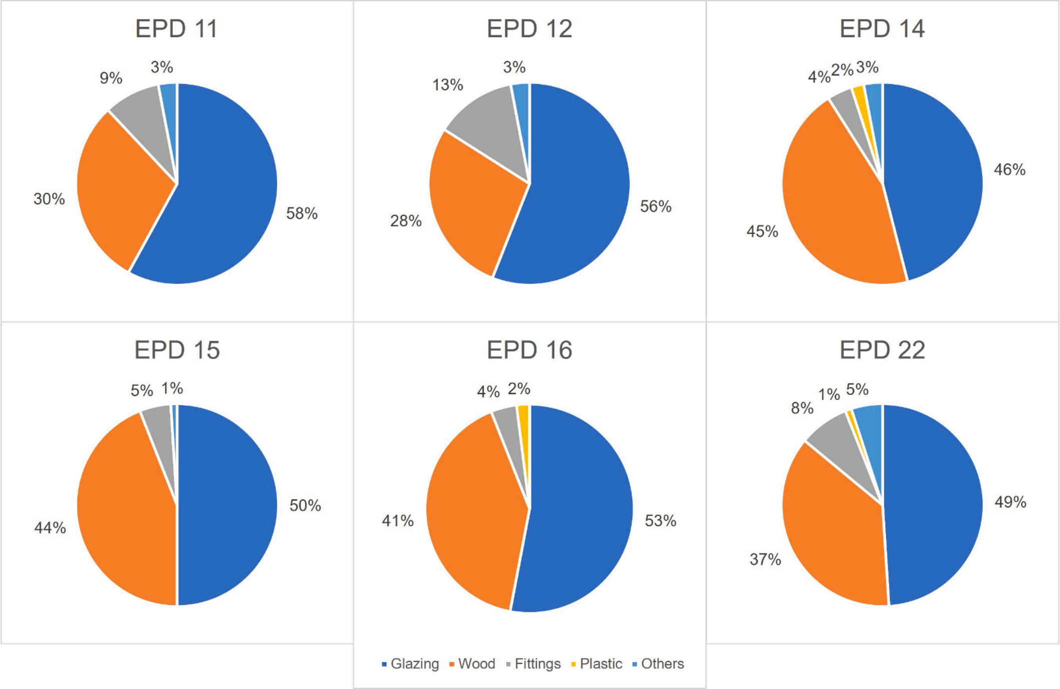

Fig. 5. Percentage contribution by weight of the three main window components compared to the total window weight (Climatic zone E, U_w-value $\leq$ 1.4).

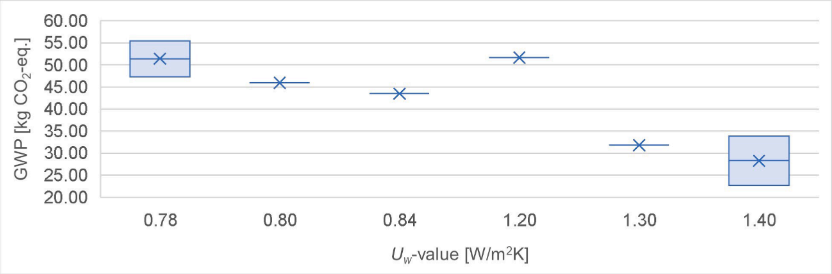

Fig. 6. Variability of GWP indicator of the product stage based on the U_w-value (FU: 1 m^2).

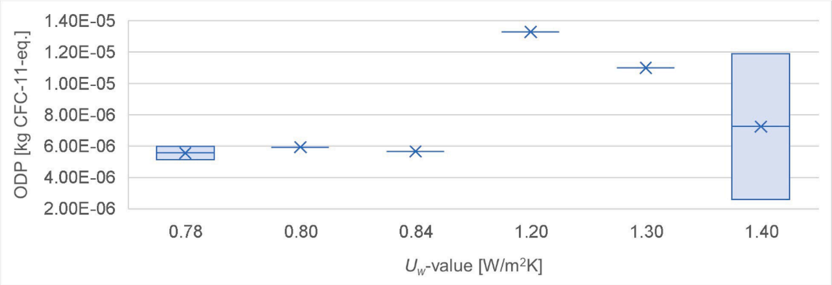

Fig. 7. Variability of ODP indicator of the product stage based on the U_w-value (FU: 1 m^2).

4.2. Maintenance phase

After defining the maintenance scenarios and the frequency of the maintenance activities, the values of the environmental impacts of each EPD per maintenance cycle were calculated. For this calculation, module B4 was neglected, as it was only considered in EPD 6.

EPD 13 had values up to four times higher than the other EPDs, as it was considering a repair scenario instead of maintenance. Therefore, this EDP was discarded. Table 19 shows the average environmental impact per maintenance stage.

The influence of location on the environmental impacts of maintenance was studied considering an average service life of 34 years. Furthermore, three Italian climate zones were selected for the analysis: climate zone B (protected weather), climate zone D (normal weather), and climate zone F (heavy weather). Further assumptions adopted were an opaque initial coating and a yearly inspection performed without using maintenance products. Then, the frequency of the maintenance activities was calculated (Table 20).

The highest impact values are for a window with a dark colour coating and located in Italian climate zone F, which is found to be three

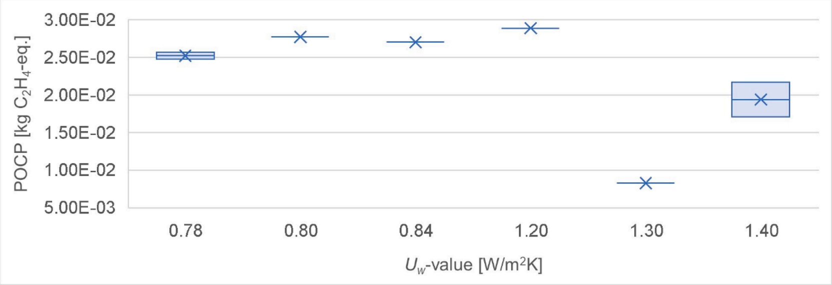

Fig. 8. Variability of POCP indicator of the product stage based on the U_w-value (FU 1 m^2).

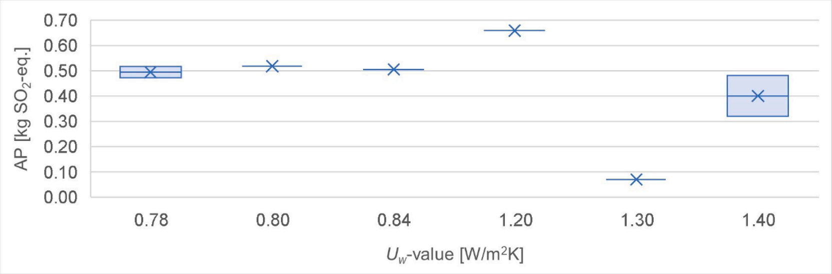

Fig. 9. Variability of AP indicator of the product stage based on the U_w-value (FU: 1 m^2).

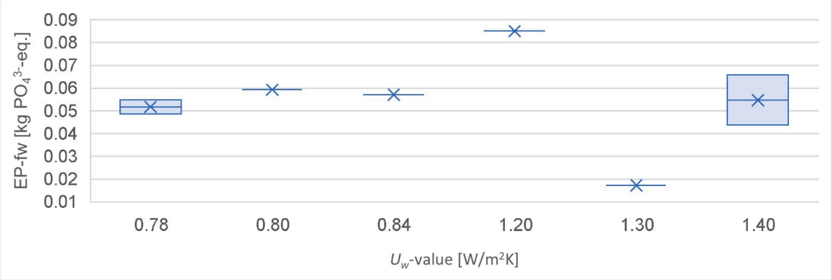

Fig. 10. Variability of EP indicator of the product stage based on the U_w-value (FU 1 m^2).

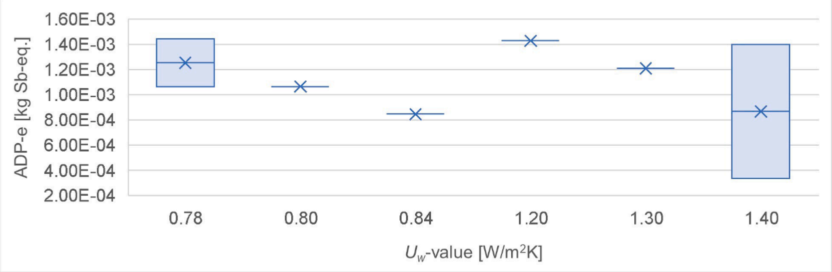

Fig. 11. Variability of ADP-e indicator of the product stage based on the U_w-value (FU: 1 m^2).

times that of the lowest case (light colour of coating and Italian climate zone B).

A sensitivity analysis was carried out considering service life variation. The same assumption of one internal maintenance treatment every 20 years was adopted, while the frequency of external maintenance treatments was taken from the maintenance scenarios defined in Table 7. This outline analysed a change in the service life between 34 years, as the average value among the collected EPDs, and 60 years, as the average value assumed in the literature [38]. A non-linear correlation is observed with the increase in the service life (Table 21). The increase in the service life is 176 %, whereas the environmental impacts vary between 200–267 % depending on the different weather exposure of the window and coating colour. However, the number of maintenance cycles and their resulting environmental impacts provide the same outcome: the maximum environmental impacts correspond to a dark coating colour and the Italian climate zone F, whereas the minimum environmental impacts are associated with a light coating colour and the Italian climate zone B. However, there is a 2.6 fold difference between maximum and minimum environmental impacts for the service life of 60 years, compared to a 3 fold for the service life of 34 years.

The changes in the environmental impacts when considering different climate zones and coating colour, and a service life of 34 years are analysed. Fig. 13 shows the environmental indicators for the Italian climate zone B for the different coating colours. In this case, the light

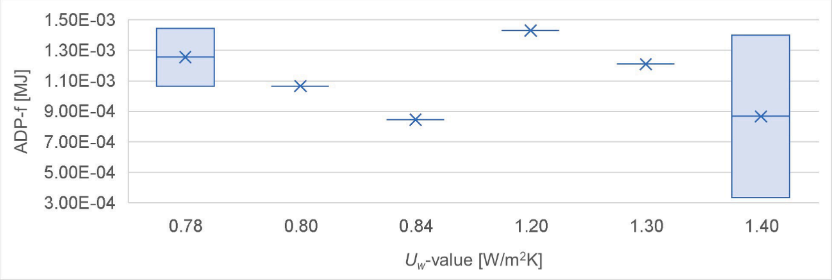

Fig. 12. Variability of ADP-f indicator of the product stage based on the U_w-value (FU: 1 m^2).

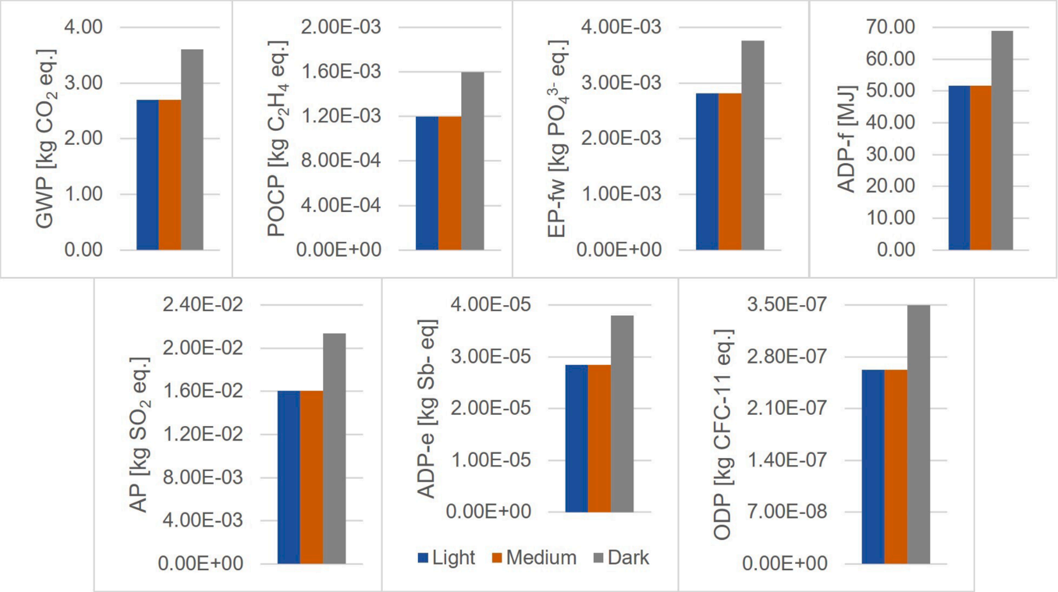

Fig. 13. Environmental indicators of the maintenance stage for the Italian climate zone B based on coating colours (FU: 1 m^2).

and medium colours share the same values for the environmental indicators and the values for the dark colour are 33 % higher.

Fig. 14 Presents the environmental indicators for the italian climate zone d with the different coating colours. in this case, the environmental impacts of the window with the light colour are 25 % lower than the values for the other colours.

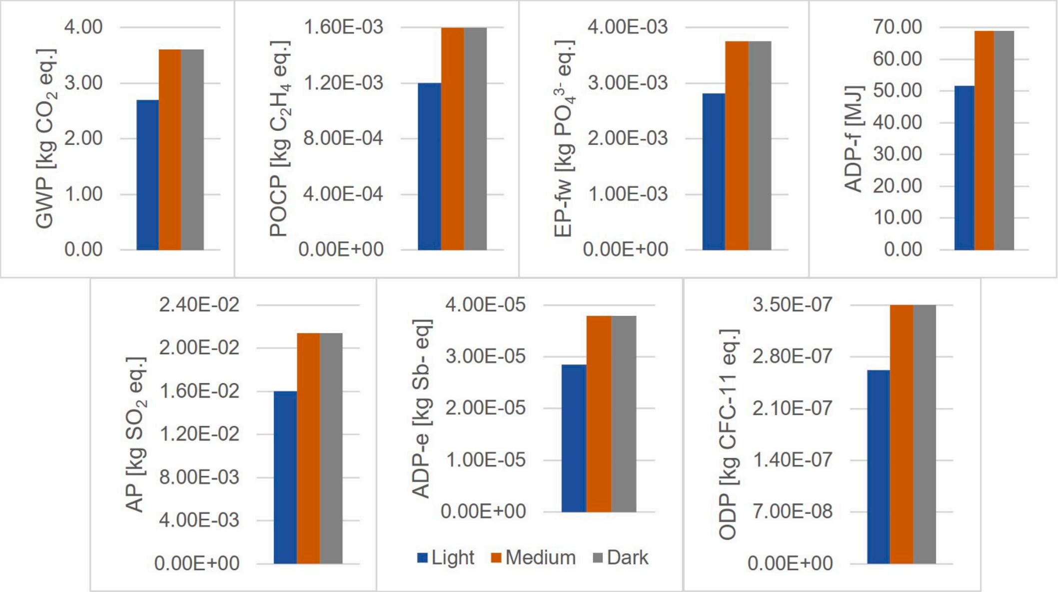

Fig. 14. Environmental indicators of the use stage for the Italian climate zone D based on coating colours (FU: 1 m^2).

The environmental indicators for the Italian climate zone F are presented in Fig. 15. The value for a window with a light coating is about 44 % lower in comparison to a window with a dark coating.

Fig. 16 shows the environmental indicators for a light coating colour in the different Italian climate zones. The environmental impacts for the Italian climate zones B and D are 40 % lower than the values for the Italian climate zone F.

Fig. 17 presents the environmental indicators for a medium coating colour. The Italian climate zone B presents the lowest values for the environmental indicators, 57 % lower in comparison to the Italian climate zone F.

Fig. 18 shows the environmental indicators for a dark coating colour. The environmental impacts for climate zone F are about 55 % higher than those for the other zones.

5. Discussion and Recommendations

This study analysed the **embedded impacts** associated with the manufacturing of wooden windows and the operational impacts related to maintenance activities during their service life. The work sought to understand how the main window components (wood, glazing and fittings type), U_w-value, size of the manufactured window frame, and manufacturer influence the environmental impacts of the product stage. Furthermore, the influence on the environmental impacts generated during maintenance of these properties, as well as service life, coating type and climate conditions was studied.

Twenty-two EPDs of wooden windows based on the European environment were collected. Of those, eleven were selected for further study, as they analyse the product and use stages and meet the specified range of U_w-values (0.78 W/m^{2}K to 1.40 W/m^{2}K). The adopted functional unit was 1 m^2 of the window surface, with a thermal transmittance performance suitable for each Italian climate and a service life of 34 years.

The results show that the most influential attributes in terms of environmental impacts are glazing, wood origin, and fittings, respectively. The first aspect assessed was the raw material supply and the wood selection, and two conclusions were made. The environmental impacts of the studied windows depend on the manufacturer. Furthermore, the provenance of the wood type significantly influences the environmental impacts, contributing approximately 50 % to the GWP, and around 30 % to the POCP, AP, EF-fw, and ADP-f indicators. Regarding glazing, which is known to significantly influence the thermal performance of the entire window, increasing the number of layers results, as expected, in a linear increase across all environmental indicators, particularly for GWP, ODP, and ADPe. Finally, fittings can increase the GWP by up to 20 % when their weight increases by approximately 50 %.

Next, the influence of change in the U_w-value was studied. The conclusion was that the higher the offset of U_w-value in EPDs, the higher the relative difference of the environmental impacts. However, a non-linear correlation was observed.

As might be expected, the case study confirms that the embedded impacts of wooden windows vary mostly with the influence of the U_w-value: the higher the offset of U_w-value between EPDs, the higher the relative difference in the environmental impacts. Fig. 19 shows the trade-off significance per environmental indicator of the product stage in each U_w-value. The correlation between all the EPDs is not linear.

Regarding **operational impacts**, only the maintenance stage was analysed. In particular, the climate conditions imply a difference in the required maintenance activities for the window. For instance, dry climates need less maintenance and lower quality of the components used to build the window to achieve the same service life compared to cold climates. Moreover, thermally treated wood usually has a longer service life than untreated wood, due to its lower moisture content, so resulting in a lower tendency to degrade and a longer service life.

Furthermore, yearly inspection of the window leads to an increase in the interval between maintenance stages and longer service life. The frequency of maintenance stages varies according to the coating type, coating colour, and climate conditions. The environmental impacts between the maximum environmental impacts for a dark colour coating and the Italian climate zone F and the minimum environmental impacts for a light colour coating and the Italian climate zone B vary up to three times for an average service life of 34 years and up to 2.6 times for 60 years.

Moreover, the operational impacts depend significantly on the colour coating and the Italian climate zone, highlighting the influence of the latter, with the highest environmental impacts for a darker colour coating and the Italian climate zone F. Fig. 20 shows the trade-off significance of the operational impacts for the three coating colours and the three Italian climate zones.

The study developed enables designers to select better window solutions by streamlined LCA based on EPDs data. The approach shown

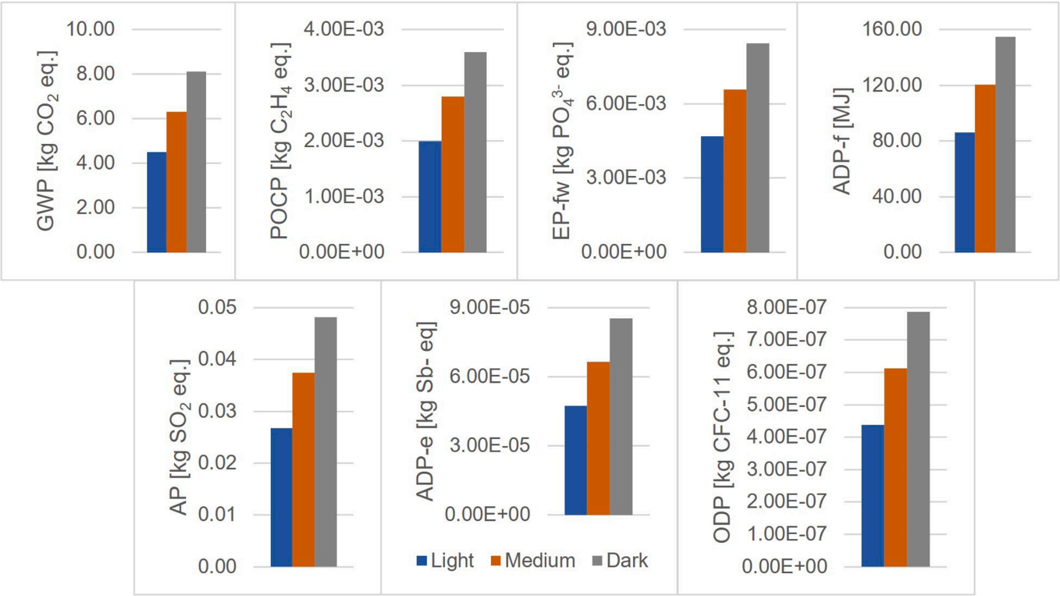

Fig. 15. Environmental indicators of the use stage for the Italian climate zone F based on coating colours (FU: 1 m^2).

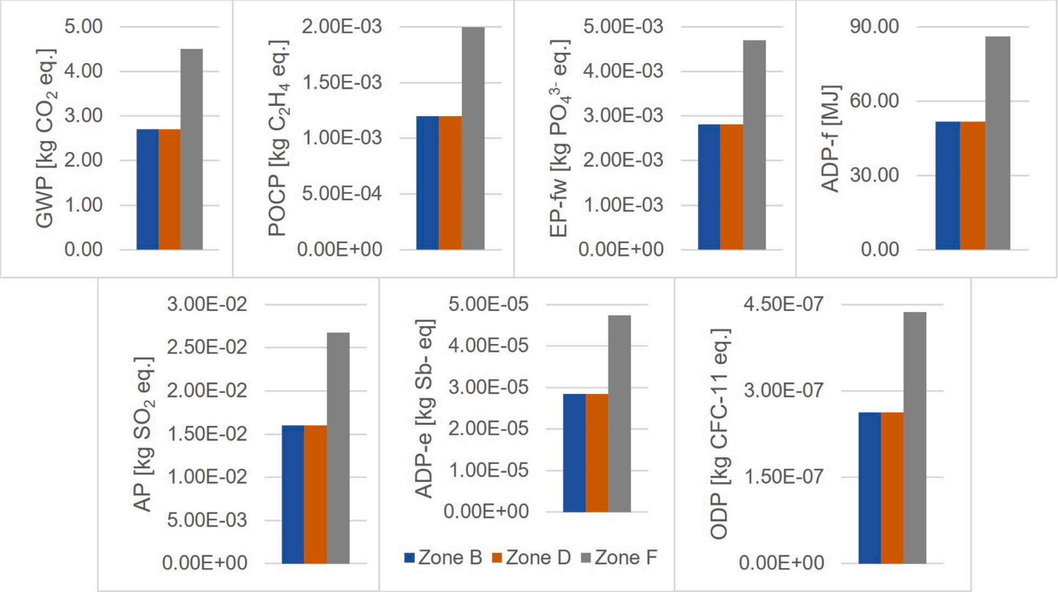

Fig. 16. Environmental indicators of the use stage for a light coating colour based on the Italian climate zones (FU: 1 m^2).

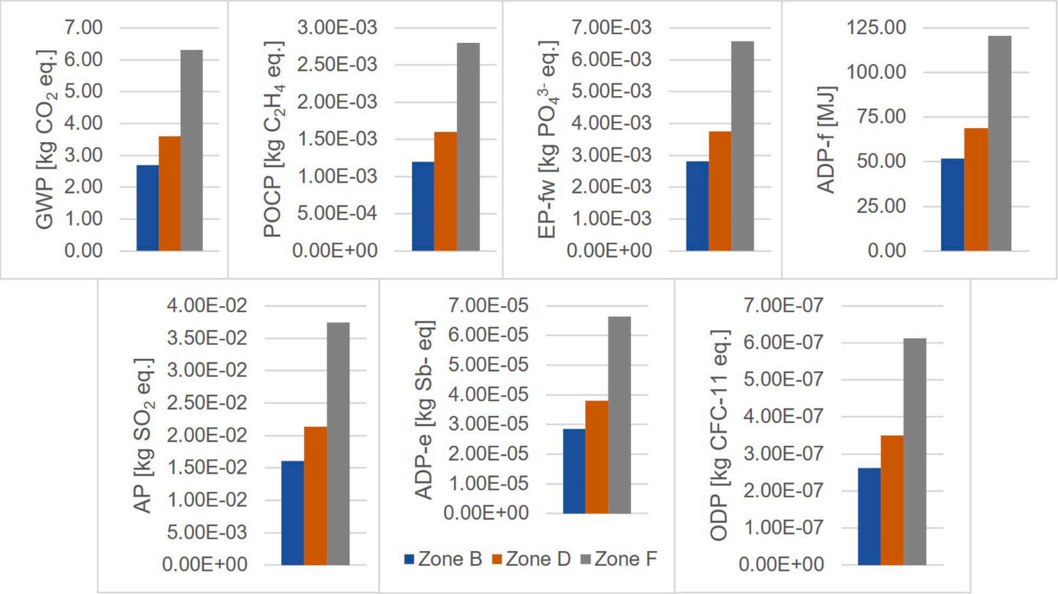

Fig. 17. Environmental indicators of the use stage for a medium coating colour based on the Italian climate zones (FU: 1 m^2).

can be further implemented with impact indicators related to end-of-life cycle stages, in addition to product and maintenance stages.

Further work could be expanded to consider other properties for the product stage, such as coating type, solar factor, window size, or window shape. The window size was considered in the analysis, but due to the lack of data in the EPDs, a definite conclusion about its influence was not possible. Moreover, the maintenance stages were limited to three of the six Italian climate zones. A future study could consider all climate zones and a more complete representation of U_w-values. In the present case, this could not be achieved due to the limited availability of published EPDs for wooden windows appropriate for dry climates (high U_w-values), as the majority of window EPDs are for low U_w-values.

Finally, the same approach could be applied in other geographical contexts such as Central and Northern Europe to validate the conclusions of this study.

CRediT authorship contribution statement

Victor Marinello Jorba: Writing – original draft, Visualization, Investigation, Formal analysis, Data collection. **Elisabetta Palumbo:** Writing – review & editing, Data curation, Validation, Supervision, Methodology, Investigation, Conceptualization. **Pamela del Rosario:** Visualization, Formal analysis. **Marzia Traverso:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

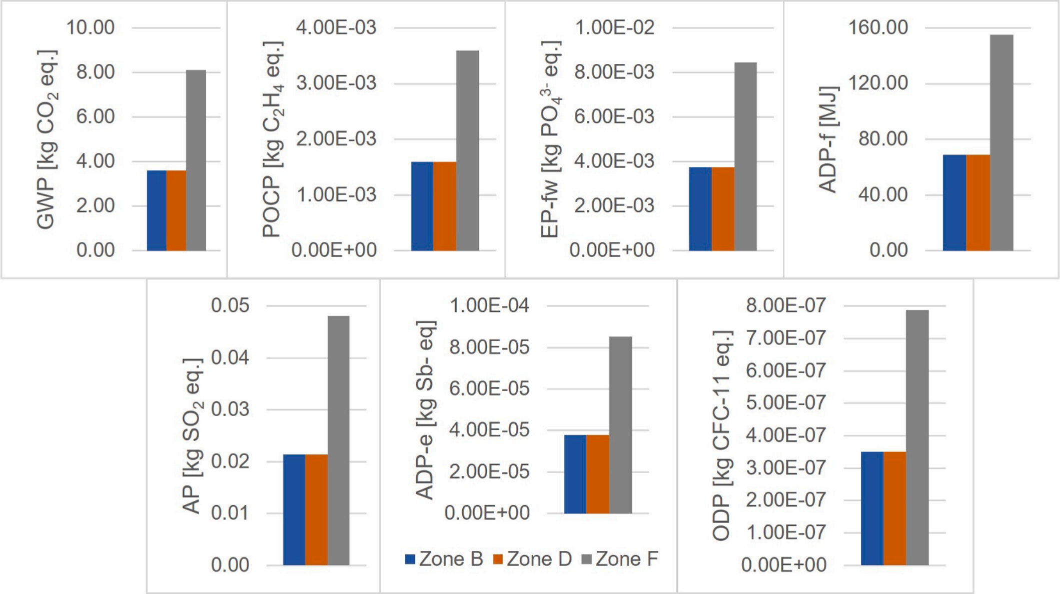

Fig. 18. Environmental indicators of the use stage for a dark coating colour based on the Italian climate zones (FU: m^2).

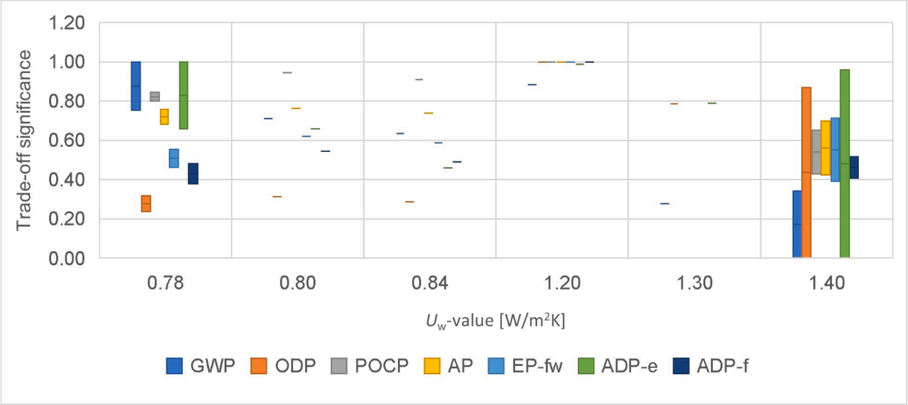

Fig. 19. Trade-off significance of the environmental indicators of the product stage for different U_w-values.

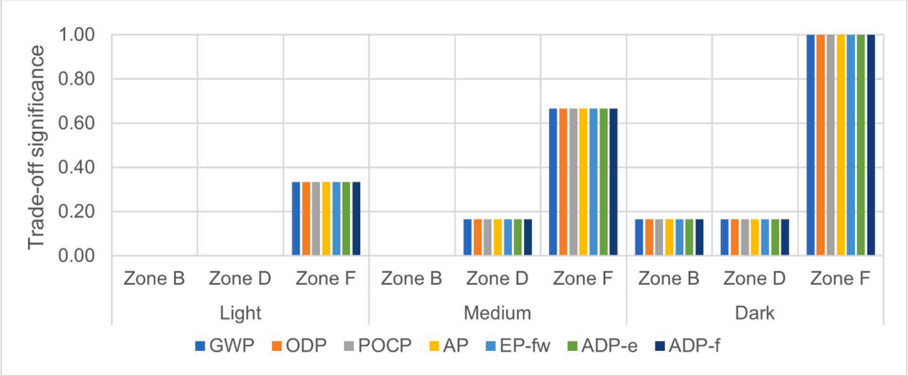

Fig. 20. Trade-off significance of the environmental indicators of the use stage for different coating colours (light, medium, and dark) and Italian climate zones (B, D, and F).

Data availability

The data used can be shared

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